

EXXON RESEARCH AND ENGINEERING COMPANY

GOVERNMENT RESEARCH LABORATORIES

REDOX BULK ENERGY STORAGE SYSTEM STUDY

Contract No. NAS3-19776

FINAL REPORT

VOLUME 1

February 18, 1976 - January 30, 1977

Exxon Research and Engineering Company
 Government Research Laboratories
 1900 East Linden Avenue
 Linden, New Jersey 07036

G. Ciprios
 W. Erskine, Jr.
 P. G. Grimes

February 10, 1977

Prepared for
 NASA-Lewis Research Center
 Cleveland, Ohio 44135

EXXON/GRU.1BH.77

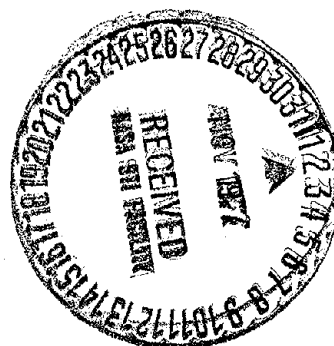
**government
 research**

(NASA-CR-135206-Vol-1) REDOX BULK ENERGY
 STORAGE SYSTEM STUDY, VOLUME 1 Final
 Report, 18 Feb. 1976 - 30 Jan. 1977 (Exxon
 Research and Engineering Co.) 200 p HC
 A09/MF A01

CSCL 10B G3/44

Unclas
51085

N77-33608



100

100

100

100

100

100

100

100

100

100

100

100

100

100

100

100

100

100

100

100

100

100

100

100

100

100

100

100

100

FOREWARD AND ACKNOWLEDGEMENT

This is the final report of Redox Bulk Energy Storage System studies carried out for the NASA-Lewis Research Center, Cleveland, Ohio under Contract No. NAS3-19776. The report is presented in two volumes. Volume 1 contains the formal discussion of the program results. Volume 2 contains the deliverable items called for in the contract, including documentation packages for several computer program simulations of the Redox battery system.

The studies were carried out by several groups within the Exxon Research and Engineering Company. In addition, personnel from the Public Service Electric and Gas Company, Newark, New Jersey, participated as consultants in the area of electric utility operation. Their efforts are acknowledged. The helpful contributions of Mr. Norman H. Hagedorn, the NASA Project Manager, are also gratefully acknowledged.

TABLE OF CONTENTS

Volume 1

	<u>Page</u>
1. SUMMARY	1
2. INTRODUCTION	4
2.1 Redox Flow Cell Battery Systems	6
3. REDOX BULK ENERGY STORAGE SYSTEMS STUDIES	9
3.1 Task I Studies - Comparative Analysis	9
3.1.1 Bibliography on Load Leveling and Peak Shaving in the Electric Utility Industries	9
3.1.2 Comparative Analysis of Candidate Electrochemical Systems	11
3.2 Task II Studies - Establishment of Systems Requirements . .	18
3.2.1 Energy Storage Applications to Meet Future Utility Needs	18
3.2.1.1 Utility Systems Analysis Objectives	18
3.2.1.2 Selection of Representative Electric Utilities	19
3.2.1.3 Amount and Distribution of Off-Peak and On-Peak Energy	20
3.2.1.4 Duty Cycle Requirements	23
3.2.1.5 Supportable Power Capacity	24
3.2.1.6 Tie-in Voltages and Power Levels for Utility Energy Storage Applications	25
3.2.1.7 Energy Storage Applications for Solar and Wind Energy	26
3.2.2 Electrical Interface Requirements	27
3.2.3 Other System Requirements, Including Economic Constraints	30
3.2.4 Comparison of Storage System Requirements and Electrochemical System Characteristics	44
3.2.4.1 Operating Duty and Storage Cycle Considerations	44
3.2.4.2 Voltage and Power Requirements	48
3.2.4.3 Economic Requirements	49
3.2.4.4 Environmental and Safety Considerations . .	52
3.3 Task III Studies - Redox Battery Model Development and Systems Analysis	53
3.3.1 Stage 1 Model Development	53
3.3.1.1 Redox System Flow Plan and Components . . .	54
3.3.1.2 Stage 1 Model Performance Characteristics and Output	59
3.3.1.3 Stage 1 Model Limitations	61
3.3.2 Stage 1.5 Model Development	67

TABLE OF CONTENTS (CONTINUED)

Volume 1

	<u>Page</u>
3.3.3 Stage 2 Model Development	68
3.3.3.1 Stage 2 Model Logic	68
3.3.3.2 Redox Cell, Stack and Trailer Design	70
3.3.3.3 Redox Kinetics and Electrochemical Performance	72
3.3.3.4 Redox Cell Mass Transfer Coefficients	74
3.3.3.5 Membrane Considerations	74
3.3.3.6 Shuntage Currents, Flow Distribution and Thermal Effects	75
3.3.3.7 Other Design and Costing Features	78
3.3.3.8 Stage 2 Model Operation and Output	79
3.3.4 Redox Energy Storage Systems Analysis	79
3.3.4.1 Redox Model Parameter Values	81
3.3.4.2 Preliminary Analysis of Stage 1 Model Predictions	81
3.3.4.3 Analysis of Daily Cycle Energy Storage Systems	81
3.3.4.4 Sensitivity Analysis for Daily Cycle Energy Storage Systems	97
3.3.4.5 Analysis of Weekly Cycle Energy Storage Systems	107
3.3.4.6 Cost Reduction Opportunities for Redox Energy Storage Systems	120
4. CONCLUSIONS AND RECOMMENDATIONS	131
5. APPENDICES	137
5-1 The Potential for Application of Energy Storage Capacity on Electric Utility Systems in the United States - Part I	138
5-2 The Potential for Application of Energy Storage Capacity on Electric Utility Systems in the United States - Part II	147
5-3 Electrical Interface Requirements	156
5-4 Selected Bibliography of Electrochemical Design References	161
5-5 Flow Distribution and Pressure Drop in Redox Cell Stacks	171
6. APPENDIX 6 - PRELIMINARY TESTING OF THE STAGE 2 MODEL	186
7. REFERENCES	188

LIST OF TABLES

	<u>Page No.</u>
Table 3-1 - Subject Index for Bibliography	12
Table 3-2 - Classification Index for Bibliography	13
Table 3-3 - Overview Comparison of Candidate Electrochemical Systems	16
Table 3-4 - Major Contending Battery Systems for Bulk Energy Storage	17
Table 3-5 - U.S. Representative Electric Systems	19
Table 3-6 - Ranges of Storage System Duty Cycle Operating Parameters Supportable on U.S. Electric Utility Systems	24
Table 3-7 - Maximum Energy Storage System Capacity (100% Efficiency) Capable of Being Supported on U.S. Electric Utility Systems	25
Table 3-8 - Tie-in Voltage and Power Level for Utility Energy Storage Applications	25
Table 3-9 - Voltage Levels In Utility Systems	29
Table 3-10 - Parametric Bounds for Integration of Energy Storage Devices Into an Electric Utility Distribution System	30
Table 3-11 - Assumptions for Battery Energy Storage Systems and Conventional Generation Used in Break-Even Economic Analysis	32
Table 3-12 - Assumptions for Utility System Operations in Break-Even Economic Analysis	34
Table 3-13 - Break-Even Capital Cost Range for Battery Energy Storage Systems in Peaking Duty	35
Table 3-14 - Break-Even Capital Cost Range for Battery Energy Storage Systems in Intermediate Duty	35
Table 3-15 - Probable Break-Even Costs for Battery Energy Storage Systems in Peaking and Intermediate Duty	36
Table 3-16 - Break-Even Cost Sensitivity Analysis for Battery Energy Storage Systems in Peaking Duty	38
Table 3-17 - Break-Even Cost Sensitivity Analysis for Battery Energy Storage Systems in Intermediate Duty	39
Table 3-18 - Reactant Storage Characteristics of Electrochemical Systems	46

LIST OF TABLES (CONT'D)

	<u>Page No.</u>
Table 3-19 - Cell Balancing Conditions	47
Table 3-20 - Sample Printout from Stage 1 Model	62
Table 3-21 - Parameters Specified in NASA Stage 1 Model Outline	82
Table 3-22 - Additional Parameters Included in Final Stage 1 Model . . .	84
Table 3-23 - Sub-System Cost Distribution for Daily Cycle Redox Battery Systems	92
Table 3-24 - Sensitivity Analysis of Baseline Redox System	99
Table 3-25 - Comparison of Weekly Cycle Analysis Using Stage 1.5 Model With Different Optimization Parameters	115
Table 3-26 - Effect of Charge Options on Analysis of Asymmetric Discharge Time Profiles	117
Table 3-27 - Effect of Charge Options on Analysis of Symmetric Discharge Time Profiles	119
Table 3-28 - Expected Levels of Sub-System Cost Reduction Factors . . .	125
Table 3-29 - Projected Cost Reduction for Daily Cycle Redox Battery System	127
Table 3-30 - Projected Cost Reduction for Weekly Cycle Redox Battery System	128

LIST OF FIGURES

	<u>Page No.</u>
Figure 2-1 - Base-Load Off-Peak Energy and Corresponding Peak-Shaving Energy for a Typical Summer Week for the PSEG Electric System	5
Figure 2-2 - The Redox Flow Cell	7
Figure 3-1 - Program Task Identification	10
Figure 3-2 - Maximum Annual Off-Peak (On-Peak) Energy Limits for U.S. Electric Utility Systems	21
Figure 3-3 - Distribution of Off-Peak and On-Peak Energy On Representative Summer and Winter Peaking Power Systems	22
Figure 3-4 - Effect of Levelized On-Peak/Off-Peak Energy Cost Ratio on Break-Even Cost for Near-Term Lead-Acid Batteries	40
Figure 3-5 - Effect of Battery Life on Break-Even Cost	41
Figure 3-6 - Effect of Battery Efficiency on Break-Even Cost	42
Figure 3-7 - Idealized Electric Utility Load Profile	45
Figure 3-8 - Comparison of Projected Investment Cost for Lead-Acid Battery Systems With Break-Even Investment Costs	50
Figure 3-9 - Comparison of Projected Investment Cost For Advanced Battery Systems With Break-Even Investment Costs	51
Figure 3-10 - Base-Line Plot Plan for Redox Storage System	55
Figure 3-11 - Schematic Cell Design for Stage 1 Model	56
Figure 3-12 - Simplified Logic Sequence for Redox System Performance Evaluation	69
Figure 3-13 - Cell Configuration Schemes	71
Figure 3-14 - Cell Flow Schemes	73
Figure 3-15 - Stack Flow Schemes	73
Figure 3-16 - Flow Scheme Through Stack	77
Figure 3-17 - Hypothetical Output Map for Stage 2 Model Results	80
Figure 3-18 - Stage 1 Model Efficiency Predictions As a Function of Charge and Discharge Time.	87
Figure 3-19 - Stage 1 Model Power Ratio Predictions as a Function of Energy Storage Efficiency	88

LIST OF FIGURES (CONT'D)

	<u>Page No.</u>
Figure 3-20 - Effect of Charge/Discharge Time on Daily Cycle Redox System Investment Costs	90
Figure 3-21 - Energy Investment Costs Look Good for Redox Case Using Optimistic Parameters	91
Figure 3-22 - Composite Display of Typical Stage 1 Model Results for Daily Cycles	93
Figure 3-23 - Effect of Scale on Redox System Investment Costs	96
Figure 3-24 - Effect of Flow Rate on Section Costs	98
Figure 3-25 - Effect of Key Parameters on Redox System Investment Cost	103
Figure 3-26 - Effect of Charge Current Density on Investment Costs . .	104
Figure 3-27 - Breakdown of Redox System Costs as a Function of Charge Current Density	105
Figure 3-28 - Optimum Charge Current Density Varies Slightly With Reversible Cell Voltage	106
Figure 3-29 - Redox System Investment Costs Respond Favorably to Increased Energy Density	108
Figure 3-30 - Redox Reactant Concentrations Required to Achieve 50 WH/L Energy Density	109
Figure 3-31 - A Hypothetical Weekly Cycle	111
Figure 3-32 - Considerable Opportunity Exists for Optimizing Daily and Weekly Redox Systems	112
Figure 3-33 - Energy Investment Costs for Batteries in Weekly Storage Cycles	114
Figure 3-34 - Reactant Inventory Profiles for Asymmetric Discharge Time Case	116
Figure 3-35 - Reactant Inventory Profiles for Symmetric Discharge Time Case	118
Figure 3-36 - Improved Redox Couples Help, but Additional System Cost Reduction is Needed to Meet Daily Cycle Targets	121
Figure 3-37 - Weekly Cycle Targets are Closer, Especially With Improved Redox Couples	122
Figure 3-38 - Projected Cost Reduction For Daily Cycle Redox Battery System	129
Figure 3-39 - Projected Cost Reduction For Weekly Cycle Redox Battery System	130

1. SUMMARY

Redox Bulk Energy Storage System studies were carried out by Exxon Research and Engineering Company for the NASA-Lewis Research Center under Contract No. NAS3-19776. The objectives of this study program were to investigate comparative advantages and disadvantages of electrochemical systems for bulk energy storage in electric utility applications; to establish detailed potential applications for Redox battery storage systems, together with the applicable system requirements and/or performance goals; and to develop increasingly sophisticated models of the Redox system for use in determining values of system parameters or design variables needed to yield attractive system characteristics.

A review of U.S. electric utility operations was carried out by Public Service Electric and Gas Company, who served as consultants to the program. This review established broad composite requirements for energy storage devices, consisting of peaking and intermediate load demands. Peaking demands occur over a daily range of 1 to 9 hrs, whereas intermediate load demands occur over a longer 9 to 14 hr. daily period. A further characterization defined daily and weekly operating cycles for storage systems. Weekly cycles are particularly attractive, because about 45 percent of the total off-peak energy for storage is available on the week-end.

The electrical interface requirements for electrochemical energy storage devices showed that they can be placed at several points in the electric utility transmission and distribution grid. Substation locations are likely initial locations, operating at the 13 kv voltage level with discharge power levels of 10-100 Mw. Plans to integrate large-scale dc battery systems into utility networks are a relatively recent development, requiring further study for specific battery systems and power conditioning equipment.

Lastly, economic requirements for electrochemical storage devices were established. Cost factors are likely to be the major determinant deciding the future role of these devices. The economic analysis was carried out by defining the break-even capital cost of near-term and long-range battery systems in competition with direct power generation alternatives, including gas turbines for peaking demands and combined cycles for intermediate demands. Rather stringent investment cost targets were defined. Investments in the 20-30 \$/KWH range may be required for high probability of acceptance and market penetration.

The assessment of available electrochemical storage systems showed that only the lead-acid battery can be considered for near-term (to 1980) application. However, this system was judged to be too costly and short-lived for wide-spread use. Likely advanced battery system candidates were defined, including: sodium-sulfur, lithium-iron sulfide, sodium-antimony trichloride and zinc-chlorine hydrate. Costs for complete advanced battery systems were ill-defined. Insufficient experience exists at the multicell level to define operating and maintenance requirements, such as charge-balancing to ensure long-life and good performance.

The cost-effectiveness of solutions to materials selection and fabrication problems remains unanswered, although no technological restraints were found that would prevent attainment of required goals in this area after extensive R and D. Available advanced battery cost projections range near the lower limits of the break-even investment targets, but more detailed studies may reveal additional investment requirements for reliable, large-scale systems.

There is a need to monitor long-range trends in utility operation, particularly the availability and cost of off-peak power. The rising scarcity and cost of fossil fuel tends to make direct power generation devices less attractive, but the resulting higher energy costs may affect utility load demand profiles. Trends in load management and off-peak pricing to smooth load profiles should be studied, because they will affect the need for peak power production and the amount of off-peak power available for charging energy storage devices. Similarly, the impact of delayed nuclear construction on the availability and cost of off-peak power must be reviewed.

A broad-based study was made to analyze the Redox battery concept. The chief feature of the Redox concept is the decoupling of energy storage and power generation functions using circulating, dissolved reactants. In turn, this permits considerable flexibility in designing systems to cover the full range of potential energy storage applications.

The analysis was carried out using relatively simple models of the Redox system, the Stage 1 Model for daily cycles and the Stage 1.5 Model for weekly cycles. The limitations of these models were defined, including the use of time-averaged performance parameters, rather than concentration-dependent performance. However, the simple models appear adequate for scoping feasibility studies, aimed at uncovering important parameter interactions and investment cost centers.

A more sophisticated Stage 2 Model of the Redox system also was developed. This model features full load-following capability with Redox cell performance variations as a function of time-varying reactant concentration. In turn, interactions between electrochemical reaction kinetics, mass-transfer and hydrodynamic conditions are included. A more comprehensive Redox cell design analysis is permitted, but here, too, the model contains only one of several alternative approaches to cell configuration. Only limited testing was carried out during program debugging, so the full capability of the Stage 2 Model remains unexplored. However, initial results were not encouraging.

A systems analysis of the Redox battery concept showed that it is economically feasible, if certain performance parameter values can be attained, and if an auxiliary component cost-reduction program can be carried out successfully. Use of relatively conservative base-line parameter values in the Stage 1 and 1.5 Models resulted in high predicted storage system investment costs, well above the break-even cost targets described earlier. Optimistic parameter values were also defined and gave very attractive systems costs. This analysis showed that there is considerable latitude in projecting parameter values that will produce cost-effective designs, although complete attainment of all optimistic parameter levels is unlikely.

The decoupled Redox system is particularly suitable for use in weekly energy storage cycles. Current component cost estimates suggest that the power-related costs of the Redox system are high and the energy storage-related costs are relatively low. Therefore, weekly cycle applications with long discharge time capability are favored.

The results of these scoping studies, together with a comprehensive sensitivity analysis, were used to identify opportunities for reducing the cost of Redox storage systems. A plan of attack was suggested for each subsystem cost center, including:

- Redox Couples - Search for couples yielding an apparent energy density in excess of 50 WH/liter, preferably 100 WH/liter.
- Ion-Selective Membranes - Continue effort to develop low cost, long-lived membranes with improved ionic selectivity.
- Reactant Tankage - Explore the use of flexible bladders.
- Filters - Develop alternative filtration approaches, including use of in-line porous filter/strainers or external sand-beds.
- Redox Cells - Optimize geometric design with low cost materials of construction.
- Pumps - Increase maximum pump capacity by carrying out detailed system pressure balance to define required discharge pressure requirements.
- Piping - Consider all-plastic piping or flexible hose.
- Heat Exchangers (Coolers) - Optimize design based on Redox cell performance trade-off studies.
- Power Conditioning - Explore opportunities for projected cost reduction in inverter/rectifier equipment.

Additional computer modelling effort also was suggested.

In summary, the studies made in this program show that the Redox battery is an attractive concept that could fill an identified need for utility energy storage systems. However, additional R and D studies are required to verify that specific electrochemical performance goals can be achieved experimentally. A number of pathways exist for reducing the cost of the Redox energy storage systems. These pathways also must be explored, to ensure that the Redox system will be competitive with other advanced battery systems and alternative power generation approaches for meeting utility peaking and intermediate load demands.

2. INTRODUCTION

The objectives of this study program were to investigate comparative advantages and disadvantages of electrochemical systems for bulk energy storage in electric utility applications; to establish detailed potential applications for Redox battery storage systems, together with the applicable system requirements and/or performance goals; and to develop increasingly sophisticated models of the Redox system for use in determining values of system parameters or design variables needed to yield attractive system characteristics.

The United States has become aware of the need to conserve energy resources and to employ energy more efficiently. An intensive reassessment of present patterns of energy utilization is underway, caused by the recent oil embargo and fuel shortages. Rapid growth in energy consumption has increased the need to improve energy management and utilization.

Electric utility operation is a key area where substantial improvements can be made. The demand for electric power placed upon utility systems has marked daily, weekly, as well as seasonal variations. A typical weekly load profile is shown in Figure 2-1. During certain periods, the maximum power output of a specific electric utility system may be heavily taxed. At other times, as much as 50% of the power producing capability may not be fully utilized. Thus, it would be highly desirable to tap and store some of this available off-peak power and to utilize it during intermediate and peak power periods. The use of storage systems, in conjunction with base load generation, provides such a capability. Storage systems have the potential to provide power at a lower cost compared with conventional methods of peak power generation. ^{(1-2)*} The need for energy storage systems for electric utilities is made even more important by the increasing number of advanced nuclear plants, which currently operate efficiently at constant power levels.

A number of technological approaches to bulk energy storage have been proposed. These include hydro-pumped storage, compressed air, thermal steam or oil, electrochemical batteries, flywheels, hydrogen storage, and superconducting magnetic storage. ⁽³⁾ Public Service Electric and Gas Company (PSE&G) recently assessed these technology options. ⁽⁴⁾ Advanced battery systems appear promising, if certain cost and operational requirements can be met. ⁽⁵⁻¹²⁾

Of course, alternative approaches exist for satisfying the peak and intermediate load demand. Power generation devices, including gas turbines, fuel cells, diesel engines, and combined cycles, can be used on an intermittent basis. These devices use liquid or gaseous fossil fuels, and would contribute, in part, to the depletion of our fuel resources. The ultimate choice between energy storage and generation devices will be based on relative economic effectiveness.

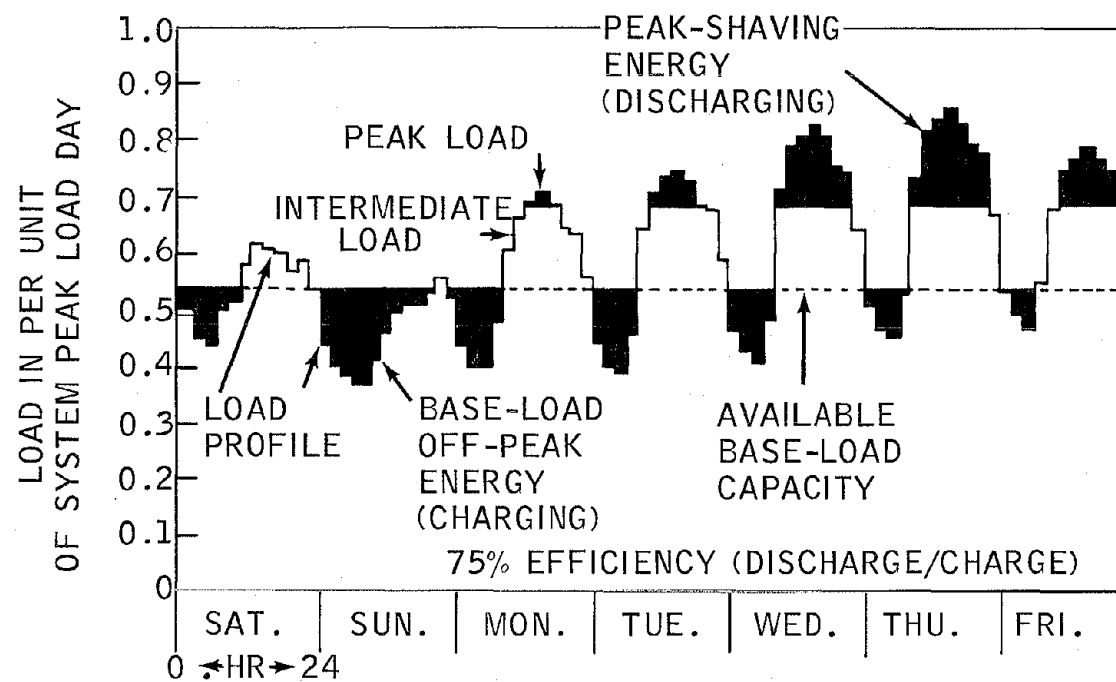
The studies carried out in this program were aimed at clarifying this comparison. In particular, these studies have focused on a new concept of electrochemical energy storage, the Redox storage battery. The characteristics of the Redox battery concept are described briefly in the following section.

7

*References listed in Section 7 of this report.

Figure 2-1

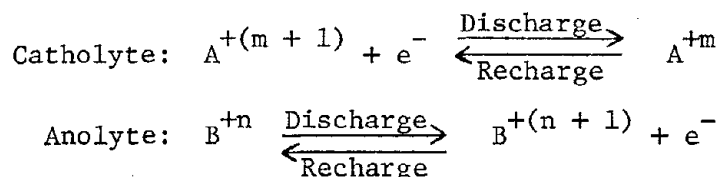
Base-Load Off-Peak Energy and Corresponding Peak-Shaving
Energy for A Typical Summer Week for the PSE&G Electric System



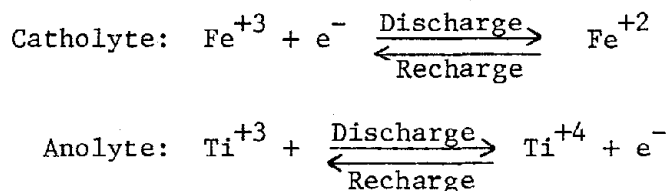
2.1 Redox Flow Cell Battery Systems

The Redox Flow Cell (RFC) system is an attractive solution to the problem of large-scale energy storage. (13-21) The RFC system consists of a group of conversion cells in which electrochemically active solutions, in the form of two soluble, highly reversible redox couples, undergo reduction and oxidation reactions. The solutions are stored separately, as anolyte and catholyte, in inexpensive bulk storage tanks. During periods of peak power demand, the charged solutions are pumped through the Redox Flow Cell and electrical energy is released. The discharged solutions are pumped back to their respective storage tanks. When off-peak power is available, the previously discharged solutions are once again pumped through the Redox Flow Cell. This time electrical energy is supplied to the cell, permitting the electrochemical regeneration or recharging of the active anolyte and catholyte species. In effect, a net amount of energy has been stored for subsequent use, as needed.

A schematic flow plan of this simple system is shown in Figure 2.2. Representative states of charge of each couple are also shown for a typical 1 electron charge/discharge reaction. In general, if "A" and "B" represent given catholyte and anolyte species, respectively, the net reactions can be written as:



An example of the redox storage concept is shown below, using the Ti^{+3}/Ti^{+4} and Fe^{+2}/Fe^{+3} couples as illustrations:

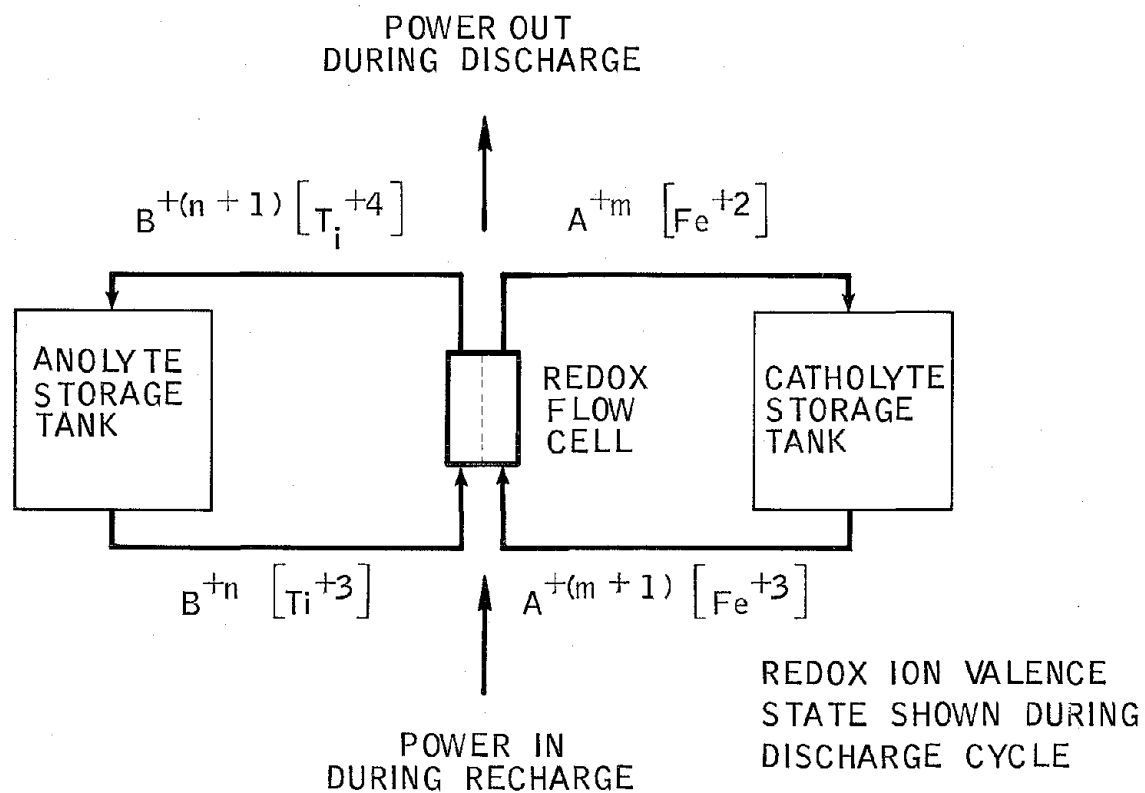


Although the illustration used cationic species as an example, anionic species (negatively charged) could also be considered.

The Redox Flow Cell itself would consist of two compartments, containing the flowing anolyte or catholyte solutions and suitable inert electrodes, separated by an ion-selective permeable membrane. The purpose of the membrane would be to ensure separation of the active ion species, thus avoiding an inefficient mixing or self-discharge loss mode during cell operation.

As with conventional battery systems, the complete Redox Flow Cell storage system would also include suitable power conditioning equipment, such as an inverter/transformer to convert the cell discharge output dc

Figure 2-2
The Redox Flow Cell



power to ac for use by the utility grid, and a transformer/rectifier to supply the dc power required during the recharge operating mode. Appropriate manifold piping, pumps and coolers, if needed, would complete the storage facility.

As described, the redox storage concept is a very appealing candidate for bulk energy storage. The potential advantages of this approach to energy storage are listed below:

- It offers cheap energy storage in the form of tanked liquids, thus decoupling the power producing and energy storage parameters that normally limit conventional "single-box" batteries to short time cycles. Redox systems should be able to accommodate weekly storage cycles, making more effective use of available off-peak energy.
- In general, redox reactions are simple and should not be kinetically limited, so that an extensive catalyst search can be eliminated. In effect, the reactions have favorable exchange currents. Minimum R&D time will be required to produce a working demonstration model. Operation at high power density will reduce Redox Flow Cell investment costs.
- The redox concept is flexible and can be adapted to a number of potential redox couples.
- In principle, high energy storage efficiencies should be achievable.
- Potentially, there are no cycle life limitations for the redox couple.
- Operation at ambient temperature might be possible, offering opportunities for reduced cost materials of construction and reduced start-up time in operation.

3. REDOX BULK ENERGY STORAGE SYSTEMS STUDIES

The studies carried out in this program were organized into three separate tasks, as outlined in Figure 3-1. In Task I, a bibliography was assembled on load leveling and peak power generation in the electric utility industry. In addition, a comparative analysis was made of candidate electrochemical systems potentially suitable for bulk energy storage. Task II consisted of a determination of the complete system requirements of energy storage devices in electric utility applications and a comparison of these requirements with projected electrochemical system characteristics. The Task III studies were concerned principally with the Redox energy storage system, including completion of a simple Stage 1 computer model and development of a more sophisticated Stage 2 model of the Redox system. The Task III studies included a parametric sensitivity analysis to define Redox system characteristics necessary to yield attractive, competitive energy storage devices.

The program effort in Tasks I and II were carried out, in part, by personnel of the Public Service Electric and Gas Company, Newark, New Jersey, who served as consultants to the Exxon Research and Engineering Company. Specific Public Service contributions to the overall program are identified in the appropriate sections of this report.

Several deliverable study items were generated during the program. In the interest of completeness, these items were assembled and are published in Volume 2 of this final report.

3.1 Task I Studies - Comparative Analysis

The Task I studies covered two areas: compilation of a bibliography on load leveling and a comparative analysis of candidate electrochemical systems for energy storage in electric utilities.

3.1.1 - Bibliography on Load Leveling and Peak Shaving in the Electric Utility Industries

A bibliography of available information on load leveling and peak power generation in the electric utility industry was compiled, with the aid of our consultant, Public Service Electric and Gas Company. Reference material was sought and compiled in the following areas:

- Current electrical power and energy usage on national regional and individual utility levels.
- Projected future power and energy requirements at each of these levels of usage.
- Descriptions of existing utility networks, including load profiles, factors and duration, generating equipment mixes, present approaches to load leveling, use of energy storage and cost analyses. Typical generator availability data (forced and maintenance outage frequencies and duration) was also compiled.

Figure 3-1

Program Task Identification

Task I. COMPARATIVE ANALYSIS

- A. Bibliography on load leveling and peak shaving in the electric utility industries.
- B. Comparative analysis of electrochemical candidate systems.

Task II. ESTABLISHMENT OF SYSTEM REQUIREMENTS

- A. Determination of applications (storage system sizes, capacities and cycling characteristics) to meet future utility needs.
- B. Electrical interface requirements.
- C. Other system requirements, including economics.
- D. Composite listing of all system requirements.
- E. Comparison of system requirements to corresponding electrochemical system characteristics for all applications.

Task III. REDOX SYSTEM MODEL DEVELOPMENT

- A. Completion of Stage 1 model.
- B. Stage 2 model development.
- C. Redox system model studies.

- Projections of future network characteristics, including factors associated with increased nuclear baseload capacity, projected load profiles, costs and implications of using solar and wind power generation.
- Detailed descriptions and comparisons of load leveling, peaking and intermediate generating systems presently in use and proposed for future use, with particular emphasis on electrochemical systems. References are included to other alternative storage technologies, such as pumped hydro, underground pumped hydro and compressed air, thermal, superconducting magnetic, kinetic, hydrogen and refrigerated water energy storage devices.

In addition to in-house files, the following source data banks were used to complete the bibliography:

- Engineering Index
- Chemical Abstract Condensates
- American Petroleum Institute (APILIT)
- Government Reports Index (NTIS)
- Smithsonian Science Information Exchange (SSIS), containing files of currently funded research.

The literature references were given an alphabetical access number and identified as to subject and classification. The specific codes employed given in Tables 3-1 and 3-2.

The bibliography also provides a discussion on the sources of current information on electric utilities. Specific data on an individual utility is available in their submissions to the Federal Power Commission, in Washington, D.C. Other sources include restricted access information provided to trade organizations, such as the Edison Electric Institute.

The bibliography, containing more than 800 references, is published in Volume 2 of this report.

3.1.2 Comparative Analysis of Candidate Electrochemical Systems

A number of electrochemical (battery) systems have been proposed as candidate technologies, potentially suitable for use as bulk energy storage devices in electric utilities. In order to place Redox storage systems in perspective, a comparative analysis was made of the alternative electrochemical system. The battery systems selected for study were:

- Lead-Acid
- Zinc-Air
- Nickel-Zinc
- Nickel-Hydrogen
- Zinc-Chlorine Hydrate
- Sodium-Sulfur
- Lithium-Chlorine
- Lithium-Sulfur
- Organic Electrolyte

Table 3-1

Subject Index for Bibliography

Subject Areas

- | | |
|-----------------------------|-------------------------------------|
| 0. Energy Storage | 6. Refrigerated Fluids |
| 1. Batteries | 7. Hydrogen |
| a. Redox | 8. Economics |
| b. Lead-Acid | 9. Electric Power and Energy Usage |
| c. Nickel-Cadmium | a. Current |
| d. Zinc-Air | b. Future |
| e. Zinc-Halogen | |
| f. Nickel-Zinc | 10. Electric System Characteristics |
| g. Nickel-Hydrogen | (Load Generation) |
| h. Sodium-Sulfur | a. Current |
| i. Lithium-Sulfur | b. Future |
| j. Lithium-Chlorine | |
| k. Non Aqueous | 11. Load Management |
| l. High Temperature | 12. Other Technology Implications |
| m. Solid Electrolyte | a. Solar Power |
| n. Sodium Chloride | b. Wind Power |
| o. Other | c. Nuclear Power |
| | d. Ocean Thermal |
| 2. Pumped Hydro | e. Geothermal |
| a. Above Ground | |
| b. Below Ground | 13. Flywheels |
| 3. Compressed Air | 14. Power Conditioning |
| 4. Super Conducting Systems | |
| 5. Thermal Storage | |
| a. Fused Salt | |
| b. Hot Oil | |

Table 3-2

Classification Index for Bibliography

Classification Areas

A	Engineering Analysis
B	Bibliography
C	Costs
E	Economics
G	General
I	Impact Areas
M	Mathematical Analysis
O	Other
P	Electric Power Systems Statistics
R	Reviews
S	System and Process Analysis
T	Technology
U	Utility System Applications

Literature on these systems was reviewed, with emphasis placed on the following factors:

- Power density
- Energy density
- Materials and availability
- Materials specific costs
- Operating conditions (temperature)
- Associated hazards (personnel and environment)
- Environmental impact
- Operational life
- Reliability
- Manufacturability

The following factors were also included:

- Dynamic characteristics, such as the effects on capacity, power output and efficiency of charging and discharging rates and depth of discharge and charge.
- Adaptability to constant power charge and discharge operations.
- Standby losses, including self-discharge and thermal losses, that could limit potential usefulness in longer term energy storage applications, such as weekend storage.
- Opportunities for recoverable costs (salvage value) at end of life. This factor will play an important role in evaluating true total costs of ownership.
- Projected maintenance costs and specific maintenance features, such as water make-up requirements, that could affect maintenance costs.
- Suitable replacement or refurbishment strategies that could affect operational life.
- Unusual auxiliary investment requirements, such as cooling fans, water make-up circuits or protective inert atmospheres that would add to installed system costs. Special power conditioning costs required to accommodate variable voltage or power output were also included.
- Multi-module characteristics that might place limits on achievable maximum module voltage or current levels, such as shuntage or parasitic current losses.
- Unusual land requirements, caused by spacial layout considerations, that might limit siting opportunities.

Considerable judgement was required in analyzing the diverse opinions noted in the data sources. In the advanced battery systems area, the state-of-the-art is generally restricted to R&D studies. Here, the information bases and degree of optimism in describing the systems and their potential varied widely. As expected, information on the lead-acid battery was the most detailed. This system is the only "fully-developed" technology, projected for use in the near future (to 1980). Here, it was found that total system cost levels were excessive. Additional discussion of the economic factors associated with bulk energy storage is presented in later sections of this report.

For the candidate advanced battery systems, technology and cost projections for scaled-up energy storage facilities were considerably more speculative. The most critical area concerns the coupling of assumed cost-effective solutions for current technological problem areas (e.g., materials of construction, membrane separators and fabrication processes) with projected operating characteristics (e.g., life, depth-of-discharge, energy density, uniformity of charge acceptance, etc). These technology-performance-cost interactions were found to be rather ill-defined.

In particular, little experience exists at the multicell level of operation, so that it is difficult to assess the longer range operating and maintenance problems of large-scale battery systems. The effects of over-charging and/or over-discharging could be serious for some battery systems. Requirements for state-of-charge indicators and control-circuitry for multiple strings of batteries are ill-defined.

Thus, realistic total installed cost estimates are not available for complete energy storage systems, fully integrated to operate reliably and safely in the utility electric grid. Current cost projections are usually restricted to estimates of material, fabrication and assembly costs for the battery modules, rather than the total system.

Highlights of the comparative assessment of candidate battery systems are given in Table 3.3. Complete details are presented in the assessment study found in Volume 2 of this report. Table 3-3 includes comments on the sodium-antimony trichloride system, which was added to the list of candidates after completion of the assessment study (22-24).

The contending systems for bulk energy storage, together with the major developers of each system, are listed in Table 3-4. The remaining electro-chemical systems were judged not suitable for this application, although they may meet the design and cost constraints imposed on vehicular (mobile) energy storage systems.

Table 3-3

Overview Comparison of Candidate Electrochemical Systems

<u>Electrochemical System</u>	<u>Positive Factors</u>	<u>Negative Factors</u>
Lead-Acid	+ Demonstrated technology	- High cost - Lead availability - Charge balancing - Maintenance
Zinc-Air	+ Potential low cost + Long life	- Low efficiency - Moderately complex
Nickel-Zinc	+ Operable	- Water loss - Zinc shape change - High cost
Nickel-Hydrogen	+ Operable	- Hydrogen storage - Thermal balance - Potential high cost
Zinc-Chlorine Hydrate	+ Potential low cost + Potential long life + Short development time	- Complex - Possible shuntage losses - Chlorine hazard
Sodium-Sulfur	+ Low cost reactants + High energy density	- Separator fabrication & life - Seal problems - Cell balancing
Lithium-Chlorine	+ High voltage + High current	- Excessive corrosion - Chlorine hazard at high temperature
Lithium-Iron Sulfide	+ Longest demonstrated life + High energy density	- Highest operating temperature - High materials costs - Lithium availability
Organic Electrolyte	+ High voltage	- Relatively unexplored area
Sodium-Antimony Trichloride ⁽¹⁾	+ Lowest molten salt temperature + Simpler seals + Highest voltage	- Antimony availability and cost - Low current density - Small cells to date

⁽¹⁾ Added system, not included in original assessment study.

Table 3-4

Major Contending Battery Systems
for Bulk Energy Storage

<u>Battery</u>	<u>Major Developer</u>
Lead-Acid	Gould ESB C and D Batteries Globe Union K-W Battery Co.
Sodium-Sulfur	General Electric Ford Dow Chemical
Sodium-Antimony Trichloride	ESB
Lithium (Silicon)-Iron Sulfide	Argonne National Labs Atomics Int. Div. (Rockwell Int'l) General Motors
Zinc-Chlorine Hydrate	EDA

In summary, no technological reasons were found for assuming that the contending systems could not be developed and optimized for bulk energy storage applications. It is clear, however, that substantial R&D programs may be required to obtain cost-effective solutions for specific problem areas, yielding operable, long-lived storage systems.

3.2 Task II Studies - Establishment of Systems Requirements

In this task, studies were carried out to define the opportunities and requirements for energy storage in electric utilities. Emphasis was placed on the requirements for electrochemical energy storage devices.

3.2.1 Energy Storage Applications to Meet Future Utility Needs

System requirements for electrochemical energy storage devices in electric utility applications were established, based on a comprehensive study performed by our consultant, Public Service Electric and Gas Company, for ERDA and EPRI (4). An overview of the approach used in this study and highlights of the results are presented below. Additional details on the methodology and results of the analysis of U.S. electric utility industry operation are given in Appendices 5-1 and 5-2, in the form of review papers authored by V.T. Sulzberger and J. Zemkoski of Public Service.

The Public Service studies, conducted in 1974-5, are based on utility data for 1971, the latest year for which complete data were available. Since this time, major incidents have occurred that will have a substantial impact on future electric utility operation. The response to the oil embargo of 1973/74 and natural gas shortage of 1976/77 will undoubtedly be reflected in future electric utility load demand patterns. Emphasis on energy conservation and load management practices, such as differential rate structures and ripple control (automatic shut-off of appliances at peak demand periods), could have a significant effect on the availability of off-peak energy for use in storage devices (25). Thorough analysis of these factors was beyond the scope of this program.

3.2.1.1 Utility Systems Analysis Objectives

The objectives of the utility systems analysis portion of this study were:

- To identify the amount and distribution of off-peak energy on electric utility systems on a seasonal, weekly and daily basis.
- To estimate the maximum amount of on-peak energy which could be supported by the available off-peak energy.
- To develop typical energy storage device duty cycles for application on U.S. electric utilities.

3.2.1.2 Selection of Representative Electric Utilities

The methodology used to meet these objectives involved statistical analyses of U.S. electric utility industry system load and generation data. To reduce the large number of utilities to a manageable sample, six electric utility systems were selected as representative of a wide range of electric utilities throughout the U.S. Data for 199 privately and publicly owned systems representing about 90% of the total installed capacity and about 97% of the net energy generated in the U.S. were analyzed in selecting the sample systems. The factors considered in the selection of the representative systems included average system size, season of system peak, annual system load factor, daily load shape (peak to valley load ratios), generation mix, and regional representation of the U.S. The six representative systems, as well as a power pool and a member company of the pool, used in the study are coded by letter designations in Table 3-5. The summer peaking systems A, B, and C are representative of the southern regions of the U.S. with system peak loads in the range of 2000 to 7000 megawatts. The winter peaking systems A', B', and C' are representative of the northern region of the U.S. with annual peak loads in the range of 600 to 2000 megawatts. The power pool, Z, and the member company, Y, are summer peaking systems (26).

Table 3-5

U.S. Representative Electric Systems

Time Of System Peak	Annual Load Factors (%)		
	Low	Average	High
Summer	A 48	B 60	C 68
Winter	A' 55	B' 63	C' 78
Summer	UTILITY (member of power pool)		Annual Load Factor Y 54
Summer	POWER POOL		Z 61

3.2.1.3 Amount and Distribution of Off-Peak and On-Peak Energy

For each representative system, the amount and distribution of off-peak energy associated with base-load capacity levels were determined by computer analysis of actual hourly load data. Capacity levels were adjusted on a seasonal basis for both maintenance and forced outages of the base-load generation units to provide a realistic indication of the off-peak energy available (27,28).

Figure 3-2 shows the total amount of off-peak energy available and the associated on-peak energy requirements for the various assumed baseload capacity levels, ranging from 40% to 100% of system peak load for U.S. electric utility systems. The negatively sloping solid lines indicate the amount of off-peak energy available on utilities with various assumed installed base-load capacity levels, while the positively sloping dashed lines indicate the on-peak energy requirements of utilities above the assumed installed base-load capacity level. For example, for a system with a 60% annual load factor with installed base-load capacity of 70% of peak load, the amount of off-peak energy available is about 8% of the annual system energy produced for load. The corresponding on-peak energy requirements for these same conditions would be about 12% of annual system energy produced for load.

For a specific capacity level, the intersection of the percent capacity lines identifies points for which the annual amount of off-peak energy available is equal to the on-peak energy requirements. The curve drawn through these points of intersection identifies, for any system, an estimate of the maximum amount of on-peak energy that could be supported by off-peak energy and the required base-load capacity level for this condition. For example, for a 60% annual load factor system, the maximum amount of supportable on-peak energy is approximately 10% of total annual energy produced for load and the associated base-load capacity level is 73% of peak load. Since electric utilities with annual load factors falling in the 55-65% range produce about 80% of the electric energy in the U.S., the maximum amount of on-peak energy that could be supplied from off-peak energy sources is estimated to be about 10% of the total annual energy produced for load.

For these maximum level conditions, the distributions of the available off-peak energy and on-peak energy needs for the representative systems on a seasonal, weekly and weekday basis are shown in Figure 3-3. The off-peak energy is relatively evenly distributed over the entire year. This is the result of the scheduling of base-load generator maintenance outages to fill seasonal load valleys. As a percent of total annual off-peak energy, the typical seasonal, weekly, and weekday distribution of off-peak energy is approximately 25%, 2% and 0.2% respectively.

Figure 3-2

Maximum Annual Off-Peak (On-Peak) Energy
Limits for U.S. Electric Utility Systems

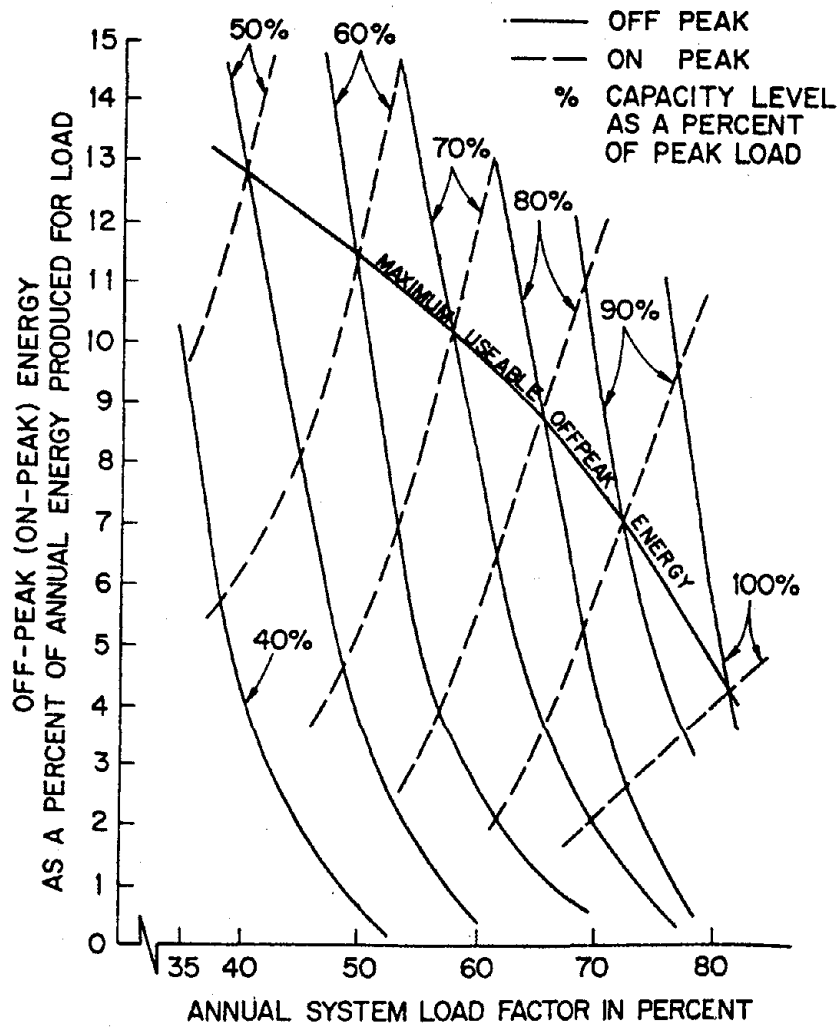
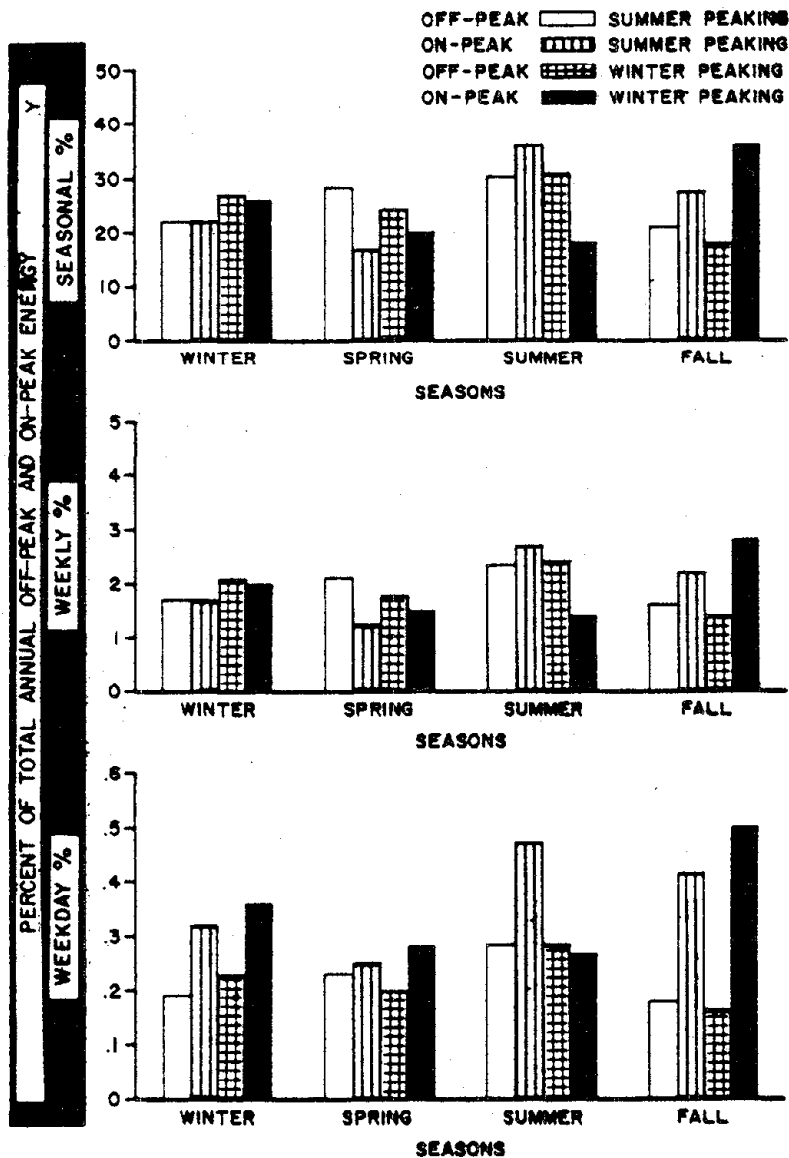


Figure 3-3

Distribution of Off-Peak and On-Peak Energy
On Representative Summer and Winter Peaking Power Systems



The weekly off-peak energy was found to be divided between the five weekdays and the weekend on a 55/45 percentage split. More off-peak energy was found to be available on an average Sunday (0.5%) than on an average Saturday (0.4%).

The distribution of on-peak energy requirements as a percent of total annual on-peak energy is about 25%, 2%, and 0.35% on a seasonal, weekly and weekday basis respectively. The amount of on-peak energy required on a Saturday and Sunday was found to be almost negligible. The ratio of on-peak energy requirements on weekdays to the on-peak energy requirements on weekends is about 93 to 7.

3.2.1.4 Duty Cycle Requirements

The very even distribution of both off-peak and on-peak energy on a daily and weekly basis throughout the year favors the application of energy storage systems designed to operate on the daily or weekly cycle rather than the seasonal cycle. The fact that nearly one-half (45%) of the off-peak energy is generally available on weekends shows the need for energy storage systems designed to operate on the weekly cycle.

Detailed analysis of the magnitude, duration, and frequency of occurrence of the available off-peak energy and the on-peak energy requirements were used to develop duty-cycle parameters for energy storage systems applicable on U.S. electric utility systems. Four possible energy storage system duty cycles analyzed for utility application included the following:

- Intermediate Duty
 - + Daily Cycle
 - + Weekly Cycle
- Peaking Duty
 - + Daily Cycle
 - + Weekly Cycle

Table 3-6 shows the possible ranges of duty cycle operating parameters for energy storage systems with a 75% overall efficiency which are capable of being supported on U.S. electric utility systems. The charge/discharge power ratios and the storage requirements provide guidance for energy storage research and development.

All energy storage systems capable of operating within the range of combinations of charge and discharge time periods of Table 3-6 are technically suitable for application on electric utility systems.

Table 3-6

Ranges of Storage System Duty Cycle
Operating Parameters Supportable on U.S. Electric Utility Systems

<u>Duty Cycle</u> <u>Characteristics</u>	<u>Type of Operation</u>			
	<u>Intermediate Duty</u>		<u>Peaking Duty</u>	
	<u>Daily</u> <u>Cycle</u>	<u>Weekly</u> <u>Cycle</u>	<u>Daily</u> <u>Cycle</u>	<u>Weekly</u> <u>Cycle</u>
Discharge Time (hrs/day)	9-14	9-14	1-9	1-9
Charge Time (hrs/day)				
Weekday	5-9	5-9	5-9	5-9
Weekend	--	14-34	--	14-34
Charge/Discharge Power Ratio ⁽¹⁾	1.3-3.7	0.8-2.4	0.15-2.4	0.1-1.5
Storage Capability (hours)	9-14	17-47	1-9	2-30
Annual Operation (hours)				
(Annual Discharge Time)	2300-3600	2300-3600	250-1000	250-1000

⁽¹⁾ For storage systems with turn-around efficiency of 75 percent. Consult Appendix 5-2 for calculating power ratio for other efficiency levels.

3.2.1.5 Supportable Power Capacity

The amount of energy storage system power capacity that can be supported depends on the system generation application, the type of duty cycle, the assumed base-load capacity level, and the energy storage system overall efficiency. For the maximum system conditions depicted in Figure 3-2, the amount of power capacity capable of being supported by U.S. electric systems is summarized in Table 3-7.

The table shows that more energy storage megawatt capacity can be supported on U.S. electric systems for the peaking application than for the intermediate application because of the generally shorter discharge times associated with the peaking mode. In addition, use of the weekly cycle substantially increases the amount of capacity the energy storage system is capable of supporting for either the peaking or intermediate generation modes.

Table 3-7

Maximum Energy Storage System Capacity
(100% Efficiency) Capable of Being
Supported on U.S. Electric Utility Systems

<u>Duty Cycle</u>	<u>System Application</u>	
	<u>Intermediate Duty</u>	<u>Peaking Duty</u>
	<u>% of Peak Load</u>	<u>% of Peak Load</u>
Daily	8	14
Weekly	12	20

3.2.1.6 Tie-in Voltages and Power Levels for Utility
Energy Storage Applications

The applications listed in Table 3-6 can be further characterized as to probable discharge power level. Each application, intermediate and/or peaking duty, and daily and/or weekly cycles, can be installed in several places within a utility distribution grid. Each location, in turn, would have an associated tie-in voltage and power output level. These latter parameters are listed in Table 3-8. Large "central station" facilities are included because there are energy storage technologies, such as pumped hydro, that are suitable for this application level. Conventional battery electrochemical systems probably would not be attractive in central station locations.

Table 3-8

Tie-in Voltage and Power Level
for Utility Energy Storage Applications

<u>Storage System Location(1)</u>	<u>Connection(Tie-in) Voltage, kv</u>	<u>Discharge Power Level, MW</u>
Sub Station	4-34.5	10-100 ⁽²⁾
Switching Station	26-230	10-200 ⁽²⁾
Central Station	138-500	500-2000 ⁽³⁾

- (1) Intermediate and peaking duty, daily and weekly cycle storage systems all appear to be useful at each location.
- (2) The larger power levels would probably apply to weekly storage cycles.
- (3) The larger power levels represent the maximum power associated with current pumped hydro storage technology.

3.2.1.7 Energy Storage Applications for Solar and Wind Energy

At the request of the NASA Project Manager, the energy storage applications associated with new forms of energy generation was explored, including: solar thermal electric, solar photovoltaic and wind generation. The analysis of the U.S. electric utility industry described earlier involved the storage of off-peak energy obtained from "conventional" base-load generation equipment, such as coal-fired steam plants and nuclear plants. Applications for energy storage will most certainly exist for "off-peak" energy produced by the advanced generation systems. The analysis of applications in these areas was hampered by the relative lack of published information on projected large-scale system operation.

It was established that for central stations:

- Solar thermal electric station designs appear to be in the 50-500 MW range, with projected operation of about 10 hrs/day, based on solar insolation characteristics.
- Solar photovoltaic systems are in the 100-1000 MW (peak rating) range, operating as above. Here, output voltage remains constant, but operating current varies with time.
- Wind generators appear to involve smaller individual units, with a peak output of about 2 MW, although larger coast-line assemblies have been described (29-37). Coupled solar/wind generation has also been suggested. Wind generators generally operate over a range of wind velocity, with rotor speed affecting the output voltage between a low, threshold level and a high, cut-off level.

A major problem will occur in modelling these energy sources as inputs to the Redox computer models. For the "solar" sources particularly, maximum generation capability overlaps maximum load demand, so that a substantial fraction of the energy produced can be fed directly into the electric utility grid. Only a fraction of the total energy produced has to be stored, provided that the solar device is a small fraction of the system generating capacity. Of course, the solar thermal systems can also use thermal storage devices, a further complication. No convenient way was found to estimate the probable energy storage requirements.

For wind generation, significant amounts of energy can be generated at night. Here, an electrochemical energy storage device would clearly be useful.

It appears that analytical systems studies of these new energy sources are not yet available in useful form. There is an acknowledged need for some form of energy storage device to be coupled to intermittantly supplied solar or wind energy. (29) However, detailed studies matching generation availability profiles with utility load demand profiles have not yet been carried out. These profiles can coincide, making it possible to deliver energy directly into the utility distribution grid. Energy storage devices would be used to cover periods of mis-match.

The most extensive review of wind generation characteristics appears to be that of Simmons (30), who evaluated the prospects for wind power in the Southern Great Plains area of the U.S., including Texas. He found that:

- Average wind speeds were high and consistent year-round, with peaks in the spring. "Correct" anemometer placement and calibration are critical factors in obtaining accurate quantitative estimates of available wind energy.
- These winds occur during the day and night, with small diurnal variations, suggesting a clear need for energy storage when the wind generators are coupled with utility systems exhibiting either daytime peaking loads (air conditioning) or night-time peaking loads (electric heating).
- The duration of calm periods is short and the frequency is erratic, again indicating the need for some form of associated energy storage to provide reliable service.

In summary, specific, definitive studies were not found that could be used to provide probable charging and discharging power/energy profiles for energy storage systems associated with wind generators. This is a fruitful area for additional study involving analysis of matched wind velocity patterns and utility operation. As these studies become available, it will be possible to use the derived charge/discharge profiles as input to the advanced computer models of Redox system operation. On the other hand, the model costing procedures are valid only for "utility-type" installations, with their associated size (>1 MW) and standards of construction. These costing procedures, described in later sections of this report, are inappropriate for estimating the cost of "residential type" installations, with their less stringent fabrication and installation standards.

3.2.2 Electrical Interface Requirements

An analysis was made of the electrical interface requirements for integrating energy storage devices into an electric utility distribution system. This analysis is given in Appendix 5-3, in the form of a report by J. Pirrong of Public Service Electric and Gas Company. The following interface requirements were covered:

- Voltage level
- Frequency
- Reactive power requirements
- Harmonics
- Radio interference
- Faults
- Auxiliary power requirements

A brief review of the importance of these electrical interface requirements is given below. These parameters were approached on a universal basis. The effect of the energy storage system on existing power system equipment must be minimized. This approach to interface requirements acknowledges the substantial investment that exists in distribution equipment; attempting to modify a distribution system to incorporate an energy storage system would not be practical or economic. Generally, broad-based requirements can be stated; specifically, the effect of each storage/converter system would have to be examined for compliance within a range of nominal parameters.

Of first consideration in interface requirements is the establishment of ac voltage levels and the establishment of the variation of this voltage about a nominal level. Such variations would occur with battery systems having performance characteristics that vary with reactant concentration. Similarly, the establishment of a nominal frequency and its variation is necessary. Ideally, the device should input only real power into the distribution network. This would dictate a unity power factor for the device, a concept that is difficult, if not impossible to achieve in real life conversion equipment. Therefore, the amount of reactive power that could be absorbed by the distribution system, must be established.

Establishment of maximum harmonic voltages and currents developed by the storage system and injected into the distribution system is of major concern. Historical limits to acceptable harmonic levels may be outdated by closer coupling of power and communication circuits, and by the incorporation into the communication network of devices sensitive to harmonic related interference. Similarly, the allowable levels of radio interference must be determined.

The dc equipment must be protected from faults and switching that occur on the ac system. Insulation levels for the dc interfacing equipment must be established from a review of overvoltage levels on the ac system during fault conditions or lightning surges. Also, contributions of the energy storage system to ac faults must be examined in view of the distribution equipment capability and the ability of conversion equipment to withstand transient conditions. Similarly, the impact of dc faults on the ac network must be determined.

The impact of energy storage system auxiliaries on the power system must be examined. For instance, if the storage system requires large horsepower motors, the resulting voltage dip during starting may be unacceptable on a distribution system. The impact of faults within the auxiliary power system of the energy storage device would be ameliorated by use of standard protective schemes for such systems.

It appears that a separate electrical interface requirement for each "application" (peaking vs intermediate load and/or daily vs weekly cycles) will not have to be established. There was a possibility here that widely dispersed storage devices might have somewhat different requirements, depending on the level of their integration within the electric utility transmission and distribution system.

The analysis of electrical interface requirements indicated that a constant voltage is required as input into the utility system, with voltage level appropriate to the specific installation. A brief review of current trends in utility transmission and distribution practices showed that storage device output at the 13 kv level is most likely. Location of the storage device at different stages in the transmission/distribution grid would probably involve changes in transformer voltage levels only. Consequently, a simple set of interface requirements should be sufficient. Here, a major burden would be placed on the power conditioning section of the battery system. Variable transformers capable of handling substantial input voltage variations are required. This would probably be reflected in the cost of the transformers. Table 3-9 lists the voltage levels at various points in the utility grid. Additional information was given in Table 3-8.

Table 3-9

Voltage Levels In Utility Systems

<u>Functional Level</u>	<u>Approximate AC Voltage Levels, kv</u>	
	<u>Previous Practice</u>	<u>Future Practice</u>
Generating Plant		
↓ (Transmission)	138-230	500
↓ Switching Station		
↓	26	138-230
↓ Sub Station		
↓ (Distribution)	4	13
↓ Customer		

The complete set of electrical interface requirements is summarized in Table 3-10. Again, details of the analysis are given in Appendix 5-3. Of course, an appreciation of the full range of technical problems associated with the integration of large scale dc battery systems into existing utility networks is a relatively recent development. This is an area that requires further study for specific battery systems.

Table 3-10

Parametric Bounds for Integration of Energy Storage
Devices Into an Electric Utility Distribution System

<u>Parameter</u>	<u>Requirement</u>
Voltage (1-1)	13,800 V \pm 2%
Frequency	60 Hz \pm 0.1 Hz
Reactive Power Exchange with AC System	\pm 2 MVAR
Harmonics	
+ Maximum Single Voltage	< 1%
+ Maximum Total Voltage	< 3%
Radio Interference	< 100 microvolts @ 1 MHz
Audible Noise at Property Line	< 48 dBA
Basic Impulse Insulation Level (BIL)	110 kV
+ Surge Arresters	10 kV
Short Circuit Current Limit	< 110% of Rated Current

3.2.3 Other System Requirements, Including Economic Constraints

This phase of our study involved a definition of the system requirements or performance goals necessary to make electrochemical storage systems attractive. Major emphasis was placed on establishing allowable system capital costs, because this parameter is the most critical quantity affecting system competitiveness. This analysis was performed by our consultants, Public Service Electric and Gas Company. The following discussion will briefly describe the analysis methodology and approach, and will present the final results of the analysis. A detailed description of this analysis is available (4).

The widely accepted methodology for economic comparison in the utility industry is the present worth (time value of cost) evaluation. This method calculates and compares the present worth of all annual revenue requirements for the step-by-step capital expenditures of alternative plans of utility plant additions. It provides a consistent means for evaluating relative economic status on a long-term basis.

Break-even economic costs (1975 dollars) for electrochemical energy storage systems were calculated by equating the present worth of all annual costs of the conventional generation system to that of the energy storage system. The comparison is performed over the range of energy storage system duty cycles identified as being typical for representative U.S. electric utility systems for the peaking and intermediate mode of generation operation. The break-even costs represent the maximum installed capital cost for which the energy storage systems would be economically competitive with conventional intermediate and peaking generation over a long-range time period.

The assumed technical and economic parameters used to carry out the break-even cost analysis are shown in Table 3-11. Two types of battery energy storage systems were considered. Lead-acid batteries were selected as a near-term storage technology, which could be commercially prior to 1985. In addition, an advanced battery system was included, with characteristics expected for systems that would be available in the 1985-2000 time period. The conventional generation technologies used for comparison with the energy storage systems include simple cycle gas turbines for the peaking application and combined cycle units for the intermediate application.

The economic competitiveness of the battery energy storage systems was determined based on a comparison with conventional generation technologies for peaking and intermediate generation application on electric utility systems. This economic competitiveness is described in terms of break-even capital costs for energy storage systems on a \$/kW basis. To determine the break-even cost, the present worth values of all future annual revenue requirements, including fixed and variable operating (operation, maintenance, and fuel) costs, of both the conventional generation and the energy storage system were calculated over the study period and equated.

The break-even economic calculations were performed on a unit capacity (kW) basis and a time period of 25 years into the future. Time periods were selected to match multiples of the expected life of the various technologies being compared. The study period for all battery storage systems covers 25 years. The study periods for the near-term energy storage technologies begin in 1980, and the intermediate-term technologies in 1990.

Table 3-11

Assumptions for Battery Energy Storage Systems and
Conventional Generation Used in Break-Even Economic Analysis

Parameter	Conventional Generation		Battery Energy Storage Systems	
	Gas Turbine(3)	Combined Cycle(4)	Near-Term (1976-1985) Lead Acid Battery	Intermediate-Term (1985-2000) Advanced Battery
Expected Life, Yrs(1)	25	25	5-10	25
Annual Carrying Charges, %(2)	15	15	27-19	15
Efficiency				
Generation, BTU/kWh(5)	12,100-11,000	8,900-8,100	--	--
Storage, %	--	--	60-75	70-80
O&M Costs (1975 Basis)				
Fixed, \$/kW/Yr	--	--	--	--
Variable, mills/kWh	5.3	4.1	2.7(6)	2.7(6)
Installed Cost (1975 Basis), \$/kW	100(7)	225(8)	--	--

- - - - -

- (1) Assuming 200 cycles/yr or 1-2000 cycles for near-term and 5,000 cycles for advanced batteries.
- (2) Expressed as a percent of total capital cost, including interest, depreciation, taxes, and cost of money during construction (construction compound interest factor). Salvage value for lead-acid batteries taken as 25% of energy storage cost.
- (3) Unit size 100-300 MW.
- (4) Based on 255 MW unit (175 MW gas turbine + 80 MW fossil steam turbine).
- (5) Near-term to intermediate-term heat rates.
- (6) Costs assumed to be one-half of conventional simple cycle gas turbine installations.
- (7) Average industry 1975 capital cost, including equipment and installation.
- (8) Same as (7); if cooling towers required, capital cost would increase by about 20 \$/kW.

To make the results of the break-even economics applicable to the electric utility industry in general, the break-even calculations were performed over a range of estimates for the economic variables which should encompass the greater part of the electric utility industry today and in the future. The generation technology assumptions of Table 3-11, together with the system economic variable assumptions of Table 3-12 describe the range of parameters over which the break-even costs were calculated. Within these ranges, economic sensitivity analyses were also performed to determine those economic variables which might have the greatest impact on break-even economic costs for the energy storage systems for the peaking and intermediate mode of generation operation.

Fossil fuel costs (1975) were assumed to range from \$1.50/MBTU to \$2.50/MBTU in the study. In each case, a 6 percent annual escalation of fossil fuel cost was assumed over the study period.

The average incremental cost of off-peak energy on a utility system is a function of the generation mix of units used for charging energy storage systems. This incremental off-peak energy cost generally ranges today anywhere from 2 to 3 mills/kWh for individual nuclear units up to about 10 to 20 mills/kWh for the base-capacity generation mix of units. It is anticipated that on any given electric utility system with the increased use of nuclear baseload capacity, that future incremental off-peak energy costs will decrease. Because the levelized incremental cost of off-peak energy for charging energy storage systems in the future could decrease, remain the same, or increase, depending on the utility's generation expansion capacity program, levelized incremental off-peak energy costs from 30 to 5 mills/kWh were evaluated in the break-even cost calculations.

To carry out the 25 year utility system expansion study with near-term batteries, starting in 1980, it was assumed that 5 year batteries would be installed in 1980 and replaced with 10 year batteries in 1985 and 1995.

The resulting break-even capital cost ranges for battery storage systems are presented in Table 3-13 for peaking duty applications and Table 3-14 for intermediate duty applications. Each analysis was carried out over a range of assumed storage equipment operating (discharge) time, using the range of parameters given earlier in Table 3-12. In addition, an analysis was made using the baseline parameters shown in Table 3-12. The resulting break-even costs are given in Table 3-15.

Table 3-12

Assumptions for Utility System Operations
in Break-Even Economic Analysis

<u>Operating Parameter</u>	<u>Parameter Range</u>	<u>Baseline Value Assumed as Typical</u>
Annual Generation Operating Time, Hrs.		
Peaking Application	≤2,000	1,000
Intermediate Application	2,000-4,000	3,000
Fossil Fuel Cost (1975 Basis) for Gas Turbine and Combined Cycle Units, \$/MBTU		
	1.50-2.50	2.50
Installed Capital Costs (1975 Basis), \$/kW		
Gas Turbine	75-150	100
Combined Cycle	175-275	225
Escalation Rates, %/Yr		
Capital (Installed) Cost	6	6
Operation/Maintenance Cost	6	6
Fossil Fuel Cost	6-9	6
Levelized Incremental Cost of Off-Peak Energy, mills/ kWh(1)		
	5-30	20

- - - - -

- (1) Based on expected mix of generation units to be used for charging energy storage systems.

Table 3-13

Break-Even Capital Cost Range for Battery
Energy Storage Systems in Peaking Duty

<u>Annual Operating Time, Hrs</u>	<u>Nominal Battery Discharge Capacity, Hrs</u>	<u>Break-Even Capital Cost for Indicated Battery Technology, \$/kW</u>	
		<u>Near-Term (1976-1985)</u>	<u>Intermediate-Term (1985-2000)</u>
		<u>Lead-Acid Battery</u>	<u>Advanced Battery</u>
400	2	50-120	140-240
1,000	5	50-230	210-440
2,000	10	50-410	310-790

Table 3-14

Break-Even Capital Cost Range for Battery
Energy Storage Systems in Intermediate Duty

<u>Annual Operating Time, Hrs</u>	<u>Nominal Battery Discharge Capacity, Hrs</u>	<u>Break-Even Capital Cost for Indicated Battery Technology, \$/kW</u>	
		<u>Near-Term (1976-1985)</u>	<u>Intermediate-Term (1985-2000)</u>
		<u>Lead-Acid Battery</u>	<u>Advanced Battery</u>
2,500	10	20-430	330-830
3,000	12	0-490	350-950
4,000	15	-40-620	390-1,190

Table 3-15

Probable Break-Even Costs for Battery Energy Storage
Systems in Peaking and Intermediate Duty

<u>Application</u>	<u>Annual Operating Time, Hrs</u>	<u>Nominal Battery Discharge Capacity, Hrs</u>	<u>Break-Even Capital Cost for Indicated Battery Technology, \$/kW(1)</u>	
			<u>Near-Term (1976-1985)</u>	<u>Intermediate-Term (1985-2000)</u>
			<u>Lead-Acid Battery</u>	<u>Advanced Battery</u>
Peaking Duty(2)	400	2	100	210
	1,000	5	180	390
	2,000	10	310	670
Intermediate Duty(2)	2,500	10	300	680
	3,000	12	340	780
	4,000	15	410	960

(1) Using baseline parameter values indicated in Table 3-12.

(2) The incremental levelized on-peak to off-peak energy cost ratio is about 4 for the peaking duty and 3 for the intermediate duty.

This analysis indicates that as the operating hours for the battery storage system increases, the level of break-even costs increases. The relatively low break-even costs for the lead-acid battery are due primarily to the shorter expected life of 5 to 10 years, compared with 25 years for the advanced technology battery. Also, for the intermediate duty case in Table 3-14, the lower break-even cost for the lead-acid battery decreases as operating hours increase. In this case, the cost of battery operation increases faster than the operating cost for the combined cycle unit used for comparison. This low range break-even cost comparison involved a combination of economic variables that favored the combined cycle operation. These variables included 30 mill/kWh incremental cost of off-peak energy and 1.50 \$/MBTU fossil fuel cost.

An economic sensitivity analysis was performed to determine the effect of incremental changes in key economic variables on the battery energy storage system break-even capital costs for the peaking and intermediate modes of generation operation. The effects on the energy storage system break-even capital costs were evaluated for variations in the following parameters: fossil fuel costs and off-peak charging energy costs, annual hours of operation, efficiency and capital cost of conventional generation, and energy storage efficiency and life for the battery systems. These results are shown in Tables 3-16 and 3-17 and Figures 3-4 to 3-6.

Tables 3-16 and 3-17 include the baseline parameter values and the incremental changes for peaking and intermediate duty, respectively. The incremental changes in break-even capital costs should be compared with the probable values given in Table 3-12. As expected, increases in fossil fuel costs make the energy storage systems more attractive. Conversely, improvements in conventional generation efficiency or heat rate, will reduce the break-even investment cost for battery storage systems. Small variations in the remaining economic parameters had relatively little effect on the break-even costs.

It should be noted that the intermediate duty system is more sensitive to changes in fossil fuel cost and usage than the peaking duty system. This is primarily due to the longer annual operating time associated with the intermediate application.

Figure 3-4 shows the battery energy storage system 1975 break-even capital costs as a function of the ratio of the levelized (yearly average) incremental on-peak to off-peak energy costs for the peaking and intermediate generation modes. The lower energy cost ratios of Figure 3-4 correspond to off-peak energy costs of 30 mills/kWh and the upper energy cost ratios correspond to 5 mills/kWh off-peak energy.

The effect of improvements in near-term battery life or break-even costs is shown in Figure 3-5. Clearly, battery life has an important effect on permissible battery storage system investment costs. On the other hand, the effect of battery efficiency, shown in Figure 3-6, is less pronounced.

Table 3-16
Break-Even Cost Sensitivity Analysis for Battery
Energy Storage Systems in Peaking Duty

<u>Parametric Variable</u>	<u>Baseline Value</u>	<u>Incremental Change</u>	<u>Incremental Change in Break-Even Capital Costs for Indicated Battery Technology, \$/kW(1)</u>	
			<u>Near-Term (1976-1985) Lead-Acid Battery</u>	<u>Intermediate-Term (1985-2000) Advanced Battery</u>
Fossil Fuel Cost, \$/MBTU	2.50	+0.50	+35	+65
Fossil Fuel Escalation Rate, %/Yr	6	+1	+30	+90
Levelized Incremental Off-Peak Energy Cost, mills/kWh	20	-1	+3	+4
Annual Operating Time, Hrs	1,000	+100	+15	+30
Energy Storage Efficiency, %	75	+1	+1	+1
Full Load Heat Rate of Gas Turbine, BTU/kWh	12,100 (Near) 11,000 (In-Term)	-1,000	-15	-30
Gas Turbine Capital Cost, \$/kW	100	+10	+5	+10

(1) Battery systems compared with gas turbine unit.

Table 3-17

Break-Even Cost Sensitivity Analysis for Battery
Energy Storage Systems in Intermediate Duty

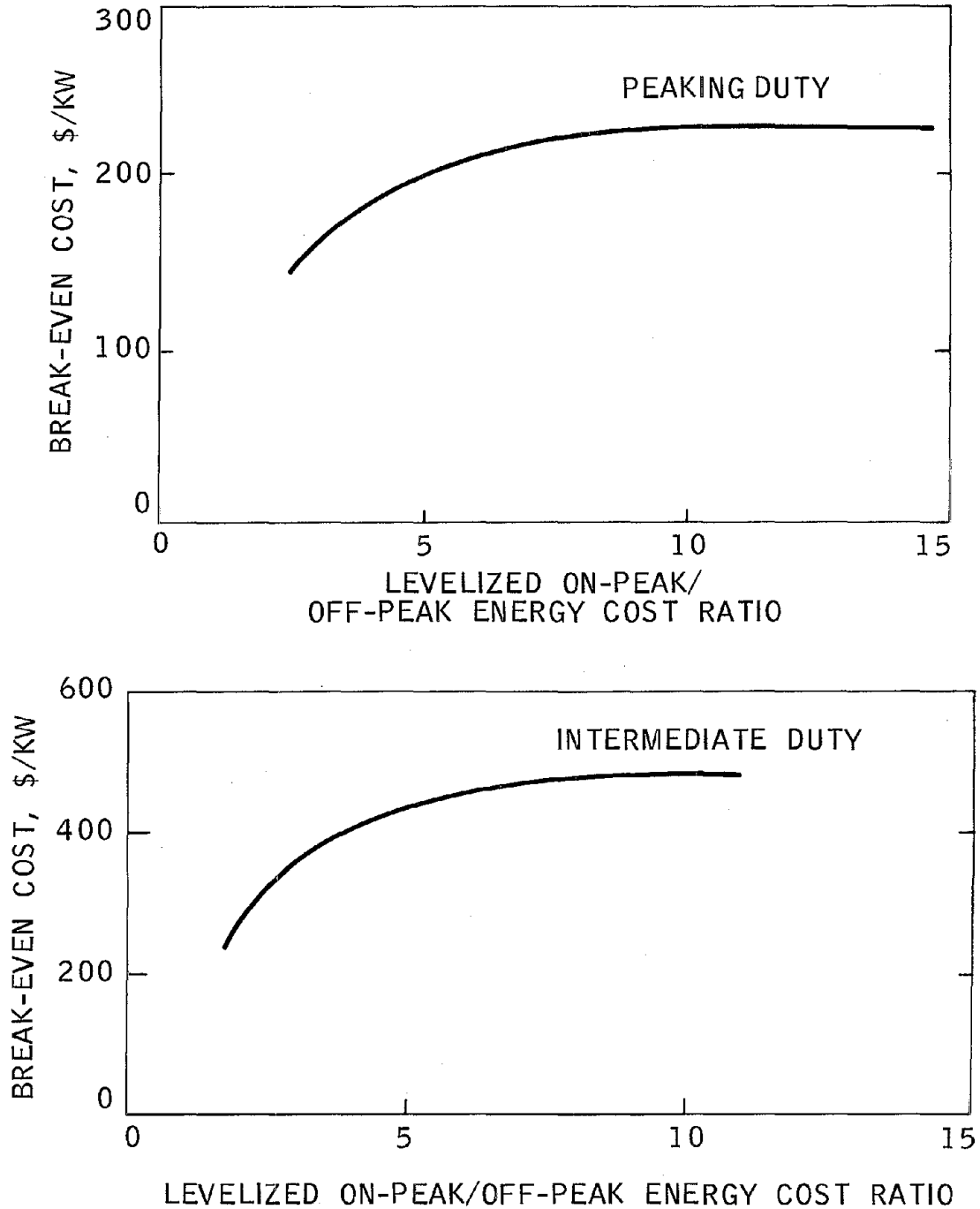
Parametric Variable	Baseline Value	Incremental Change	Incremental Change in Break-Even Capital Costs for Indicated Battery Technology, \$/kW(1)	
			Near-Term (1976-1985)	Intermediate-Term (1985-2000)
			Lead-Acid Battery	Advanced Battery
Fossil Fuel Cost, \$/MBTU	2.50	+0.50	+80	+145
Fossil Fuel Escalation Rate, %/Yr	6	+1	+65	+205
Levelized Incremental Off-Peak Energy Cost, mills/kWh	20	-1	+10	+10
Annual Operating Time, Hrs	3,000	+100	+7	+20
Energy Storage Efficiency, %	75	+1	+3	+3
Full Load Heat Rate of Gas Turbine, BTU/kWh	8,900 (Near) 8,100 (In-Term)	-1,000	-45	-90
Combined Cycle Capital Cost, \$/kW	225	+25	+13	+25

- - - - -

(1) Battery systems compared with combined cycle unit.

Figure 3-4

Effect of Levelized On-Peak/Off-Peak Energy Cost Ratio
On Break-Even Cost For Near-Term Lead-Acid Batteries

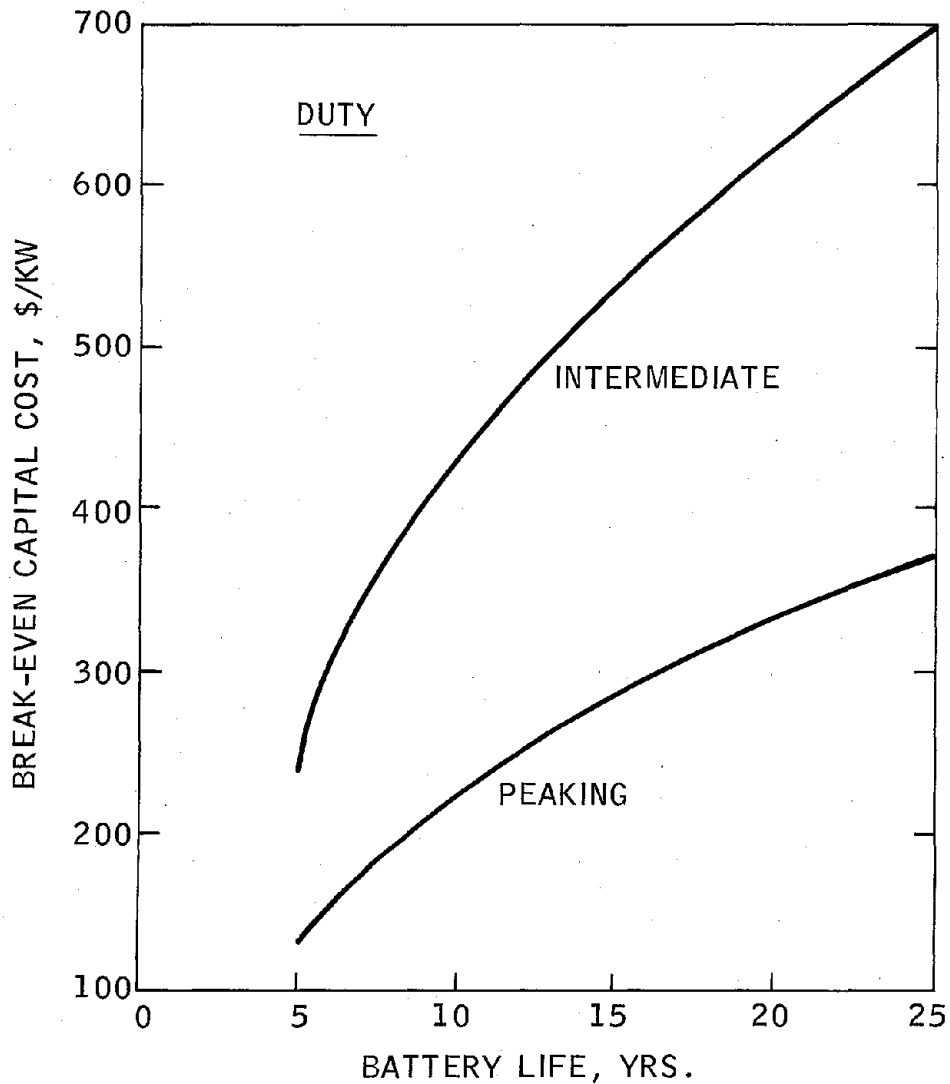


Basis:

Levelized Incremental Off-Peak Energy: 5 to 30 mills/kWh
See Figure 3-5 for remaining parameters.

Figure 3-5

Effect of Battery Life on Break-Even Cost



Basis:

Gas Turbine: \$100/kW Cost, 12,100 BTU/kWh Heat Rate,
1,000 Hours Annual Operation

Combined Cycle: \$225/kW Cost, 8,900 BTU/kWh Heat Rate,
3,000 Hours Annual Operation

Battery: 75% Efficiency

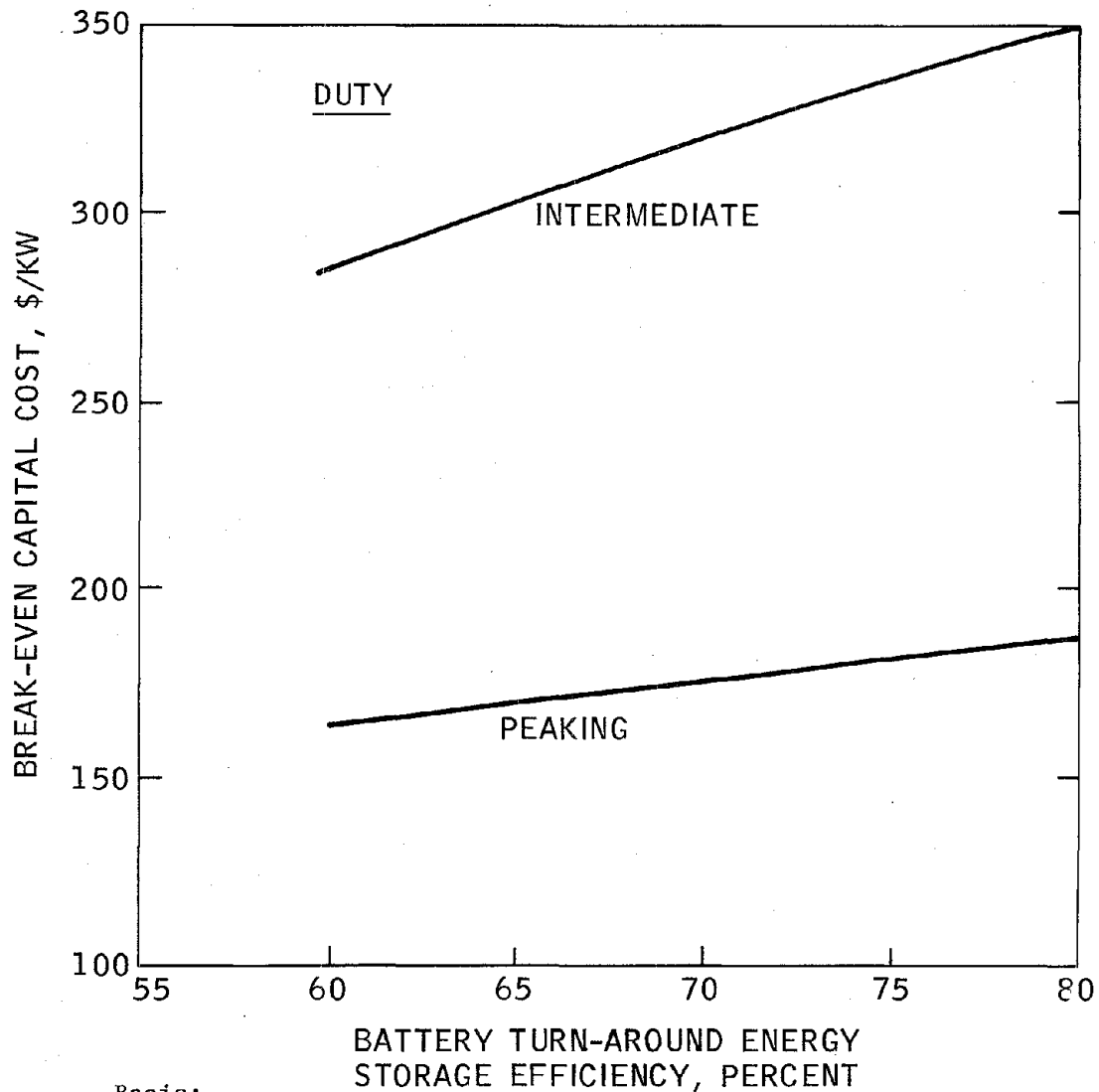
Fossil Fuel Cost: \$2.50/10⁶ BTU (1975)

Escalation: 6% per year for Capital, O&M, and Fossil Fuel

Levelized Incremental Cost of Off-Peak Energy: 20 mills/kWh

Figure 3-6

Effect of Battery Efficiency on Break-Even Cost



Basis:

Gas Turbine: \$100/kW Cost, 12,100 BTU/kWhr Heat Rate,
1,000 Hours Annual Operation

Combined Cycle: \$225/kW Cost, 8,900 BTU/kWhr Heat Rate,
3,000 Hours Annual Operation

Battery: 5, 10, and 10 years Life

Fossil Fuel Cost: \$2.50/10⁶ BTU (1975)

Escalation: 6% per year for Capital, O&M, and Fossil Fuel

Levelized Incremental Cost of Off-Peak Energy: 20 mills/kWhr

In addition to the break-even capital costs discussed above, it is possible to assign credits for expected savings in deferred or eliminated transmission and distribution line investment when energy storage equipment is located close to load centers. These credits are quite site-specific and should not be assigned on a general basis.

Summing up, this analysis of energy storage economics has developed approximate investment cost targets for candidate electrochemical (battery) systems. These economic factors will probably be decisive in determining the long-range attractiveness of battery systems. Secondary characteristics, such as overall efficiency and life or cycle life, have been factored into the analysis via their impact on expected break-even costs. We found no direct requirements or goals for the specific energy and specific power characteristics of batteries in non-mobile, large-scale energy storage applications. Of course, extremely low values for specific energy and power will show up in a detailed economic analysis via increased reactant inventories, building and land requirements.

Tentatively, it was assumed that Redox energy storage systems can be considered equivalent to the advanced batteries used in the Public Service analysis. The break-even calculations could be repeated in the future using modified parameter values that reflect expected Redox system characteristics more closely.

Lastly, this economic study was carried out using parametric variables that reflect possible ranges of future utility operation. The analysis methodology does not consider the impact of energy storage devices on the actual mix of future generation equipment. In other words, the availability of suitable energy storage devices can influence the decision process used to acquire future prime generation. A much more complicated analysis would be required to define this effect, using utility generation expansion models that simulate the future growth in capacity on a year by year basis. Further, the complete systems economic benefits that could be derived from weekly storage cycles, versus daily storage cycles, can only be inferred from the present economic study. Although both cycles could have the same annual hours of discharge operation, the respective charging operation would be quite different. The longer charging times of the weekly cycle could change the actual system investment, but **there is no simple way to estimate the credits involved for using weekend off-peak power, other than to assign a relatively lower cost for the off-peak power, compared with daily cycle operation.**

3.2.4 Comparison of Storage System Requirements and Electrochemical System Characteristics

The characteristics of candidate electrochemical systems were compared with the requirements for bulk energy storage systems. The purpose of this comparison was to highlight potential mis-match problem areas. The following discussion covers the general interactions between system requirements and battery characteristics. Individual battery systems are discussed where appropriate, based on available information. The specific characteristics of the battery systems are summarized in Table 2.10-1 (pages 89-90) in the review of battery technology found in Volume 2 of this report. Detailed discussion of the Redox system concept is not included below. Redox system characteristics are covered in a later section.

The applications and requirements for energy storage systems in electric utilities can be grouped into several areas, listed below:

- Application ranges, including operating duty (peaking or intermediate load) and energy storage cycle type (daily, weekly or seasonal).
- Voltage and power level requirements.
- Economic requirements, including capital investment cost, facility life and turn-around energy storage efficiency.
- Other factors, such as environmental and safety considerations.

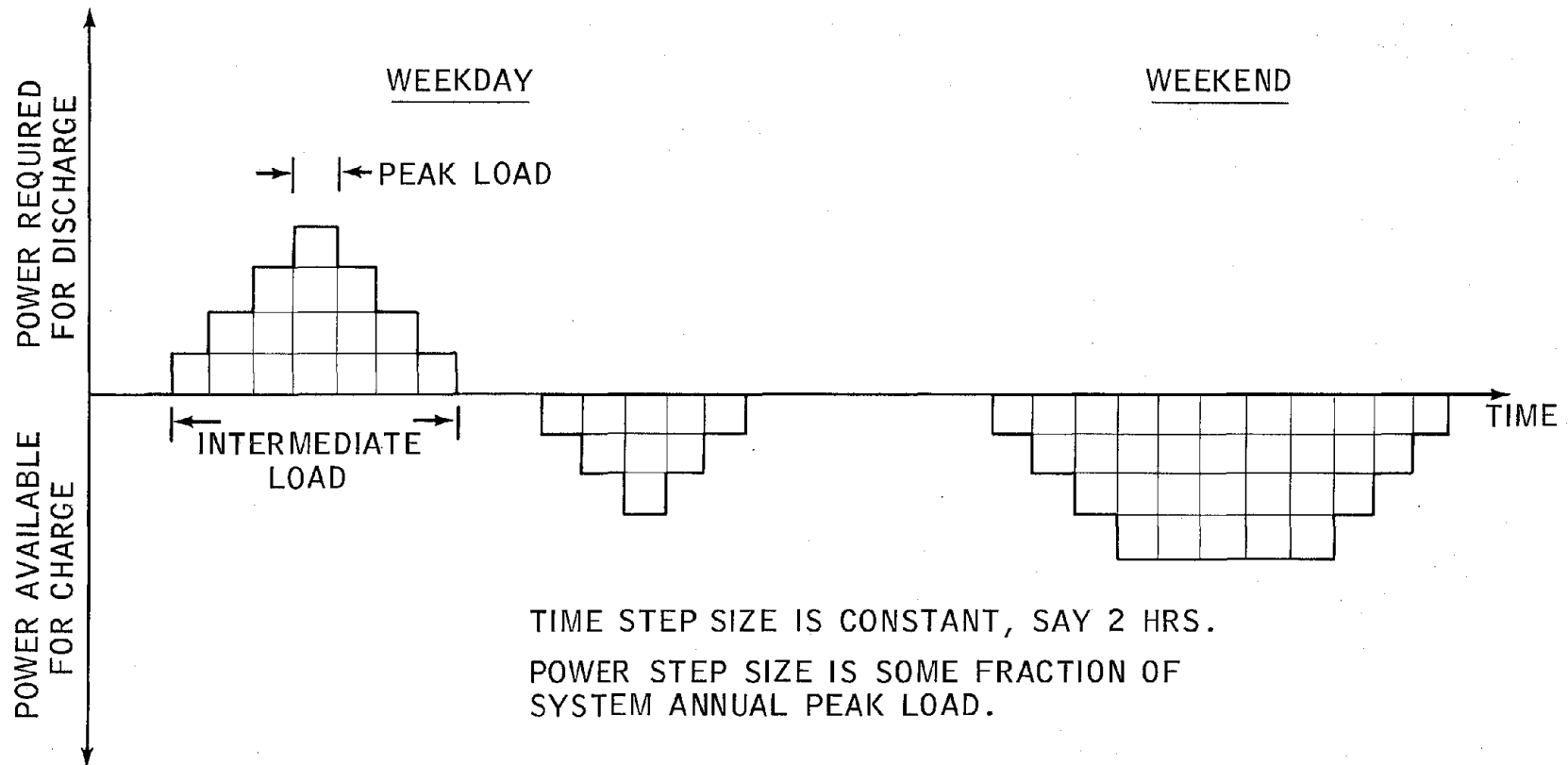
3.2.4.1 Operating Duty and Storage Cycle Considerations

The analysis of electric utilities, described earlier, showed that two general types of operations exist: intermediate load duty (requiring power delivery over relatively long daily time periods) and peaking load duty (involving power delivery over shorter daily time periods). The approximate time periods for this operation were given as broad ranges, characteristic of the U.S. electric industry as a whole. However, for specific utilities, the power profiles should be represented as sequential step-wise variations with time. An example is shown in Figure 3-7, in the form of highly idealized step pyramids, involving incremental increases or decreases in power demand or availability. Utilities must provide sufficient power to meet these variable load power demands.

Arrays of electrochemical storage devices (strings of batteries) could be assembled to supply the required power-time profile. Operationally, the entire array could be used in a "load-following" mode, with variable power output. Alternatively, individual strings of batteries could be cut into operation during the successive build-up of the demand load, with each string operating at relatively constant power.

Figure 3-7

Idealized Electric Utility Load Profile



The situation would be reversed during the off-peak charging operation. Here, it is clear that charging power also becomes available in step-wise increments. Thus, the entire battery ensemble could be recharged at variable power levels (variable rates) or individual strings of batteries could be charged at constant power, with sequential addition of strings as more power became available. In either case, the power conditioning section must be sized (and costed) for the maximum power level used. This could greatly increase the storage system equivalent energy storage cost, \$/KWH, if the equipment is used for short time periods.

A more serious concern is the ability of battery systems to accept a variable charging rate. High charge rates are generally unfavorable for chemical batteries, such as the lead-acid system, particularly when coupled with the deep depth of discharge required to increase battery utilization and minimize battery investment costs. Substantial reduction in battery life can occur, caused by specific effects of charge rate on mass and heat transfer and surface morphology within the electrode structures. Conventionally, batteries must be de-rated to accomodate these effects, resulting in higher installed investment costs. These trade-offs for the lead-acid battery are fully discussed in the battery assessment report in Volume 2.

The characteristics of the advanced battery candidates are less well-known than those of the lead-acid system. All battery systems can be classified according to their mode of reactant storage, as shown in Table 3-18. It is probable that the performance of systems retaining one or both reactants within the battery container (or electrode structure) will be sensitive to variations in charging rate. Decoupled systems, such as the Redox and slurry zinc-air batteries, on the other hand, should be less susceptible to damage. Decoupling the energy storage and power functions should allow greater flexibility to accomodate varying power profiles.

Table 3-18

Reactant Storage Characteristics of Electrochemical Systems

Reactants (Couples) Retained Within Battery Container

<u>None</u> ⁽¹⁾	<u>One</u> ⁽¹⁾	<u>Both</u>
Redox	Zinc-Chlorine	Lead-Acid
Slurry Zinc-Air	Zinc-Air	Sodium-Sulfur
	Nickel-Hydrogen	Sodium-Antimony Trichloride
		Lithium-Iron Sulfide
		Nickel-Zinc
		Organic Electrolyte

⁽¹⁾ These "dynamic" systems require some form of auxiliary power for reactant circulation.

With respect to the energy storage cycle requirements, daily and weekly cycles appear suitable for the candidate electrochemical systems. The seasonal cycle is only of theoretical interest, since very large storage capabilities would be required. Even the weekly cycles may involve excessive reactant storage for some battery systems, particularly those which retain both reactants within the battery shell. For these systems, energy storage (kWh) and power (kw) functions are coupled in a fixed ratio. These systems could scale-up approximately linearly with energy storage level. Decoupling of the energy storage and power functions, as in the Redox battery, allows a deeper consideration of storage of energy produced on the weekends.

Other comparisons in this area include load following, turn-around time and cell balancing requirements. The response time of all battery systems should be adequate to meet utility operating demands, which are generally predictable, based on many years experience. Adequate time should be available to switch in electrochemical energy storage systems, particularly the passive (static) systems that do not require auxiliary operating power. These systems were listed in Table 3-18. Dynamic (circulating or flowing) systems may require special attention. Auxiliary batteries or the main utility grid may be used to provide the start-up power for reactant pumps, air blowers, valves and cooling fans. Elevated storage of external reactants could provide a gravity flow for start-up operation. Compressed gas or air could be used to shorten the start-up time of gas electrode batteries. Proper system design should yield systems capable of handling short duration power demand transients.

On the other hand, the problems associated with cell balancing may have a severe impact on the operability and life of some electrochemical energy storage systems. All cells in an energy system are not exactly the same with respect to quantity and performance of active material. In addition, operating conditions for each cell may be slightly different. As a result, an imbalance in the state of charge of the cells may occur after some period of operation. This is particularly true for static battery systems. This imbalance must be corrected periodically to ensure system design performance and life. The general approach is to over-charge or over-discharge the system. This may be allowable in some cases and not in others. The conditions that can be used to balance a series string of some battery systems are given in Table 3-19.

Table 3-19

<u>Battery</u>	<u>Cell Balancing Conditions</u>	
	<u>Balancing Operation</u> ⁽¹⁾	<u>Operating Voltage Level,</u> <u>Volts (IR-free)</u>
Lead-Acid	Over-Charge	2.6
Nickel-Zinc	Over-Charge	2.0
Nickel-Hydrogen	Over-Discharge	0.1
Zinc-Chlorine Hydrate	Over-Discharge	-0.1

⁽¹⁾ To restore equal state of charge among cells.

Alkali metal batteries could be damaged by over-charge or discharge. Balancing these cells will probably require special procedures. Fortunately, the open circuit voltage of these batteries provides some measure of their state of charge. The sodium-sulfur battery, for example, has a sloping OCV curve for the higher states of discharge. It may be necessary to disconnect the batteries in a series string, measure the OCV and then charge/discharge the batteries to a given OCV voltage to put all the batteries into an equal state of charge.

An automatic system to balance in this manner would be quite costly and complex. Manual checking and balancing would be very costly. High temperature alkali metal battery systems may require housing under argon atmosphere. Manual cell balancing would be quite troublesome.

Use of circulating reactant systems, such as the Redox or slurry zinc-air batteries, appear to offer a clear advantage in this case. Operating and cell imbalances are normalized instantaneously by mixing the effluent reactants in the external storage system.

3.2.4.2 Voltage and Power Requirements

The tie-in voltage and power level requirements for bulk energy storage systems were defined earlier. The megawatt power levels are in general within the capabilities of battery energy storage systems, if suitably arranged in series/parallel strings, and with isolation of power conditioning equipment. Large installations could be limited by the physical size of the energy storage complex and environmental considerations but not necessarily by technology.

Analysis of the tie-in voltage showed that 13 kv \pm 2 percent is a likely value for storage systems at sub-station locations. This level would be achieved by suitable ac transformation, rather than by series connection of battery strings. Parasitic losses and safety considerations will probably limit the maximum battery system dc voltage to 1000 v or less. Here, circulating reactant batteries, having a common electrolyte path between cells and battery modules, will be at a disadvantage. Excessive shuntage power losses may limit the maximum series voltage for these systems to 200 volts or less. In turn, this will affect the cost of power conditioning equipment, as discussed in the battery assessment and Stage 1 computer model documentation, found in Volume 2 of this report. The battery assessment contains an in-depth review of power conditioning-battery interactions. In particular, the possible derating of batteries with sloping voltage-current response curves was analyzed. Power conditioning for large scale battery systems is an area that requires additional study.

From a safety standpoint, the effect of short circuits within the battery system also must be considered. The rapid failure of many cells in sequence might affect the utility grid. Fusing systems should provide adequate protection, but large scale dc switch gear can be expensive. Here decoupled energy storage/power conversion systems, such as the Redox battery, may have an inherent advantage.

3.2.4.3 Economic Requirements

The break-even capital investment costs for electrochemical energy storage systems were defined in a previous section. Economic requirements imposed on these storage systems will probably be crucial. The cost of energy storage devices has been represented by the following equation (1, 3):

$$C = C_p + C_s \times t_D,$$

where C is the installed system capital cost in \$/kw, C_p is a power-related investment cost coefficient in \$/kw, C_s is an energy-related investment cost coefficient in \$/KwH and t_D is a suitable operating time parameter, say discharge time for a daily cycle device. A review of the literature showed that value ranges for these coefficients have been estimated. The power cost coefficient, C_p , has been estimated to be 50-100 \$/kw, depending on the degree of optimism in assigning costs for power conditioning and other site-related investments. The energy coefficient, C_s , can have values of 65 to 77 \$/KwH for lead-acid battery systems (see the battery assessment in Volume 2) and 20-35 \$/KwH for advanced electrochemical systems. The latter are particularly ill-defined, as noted in an earlier section.

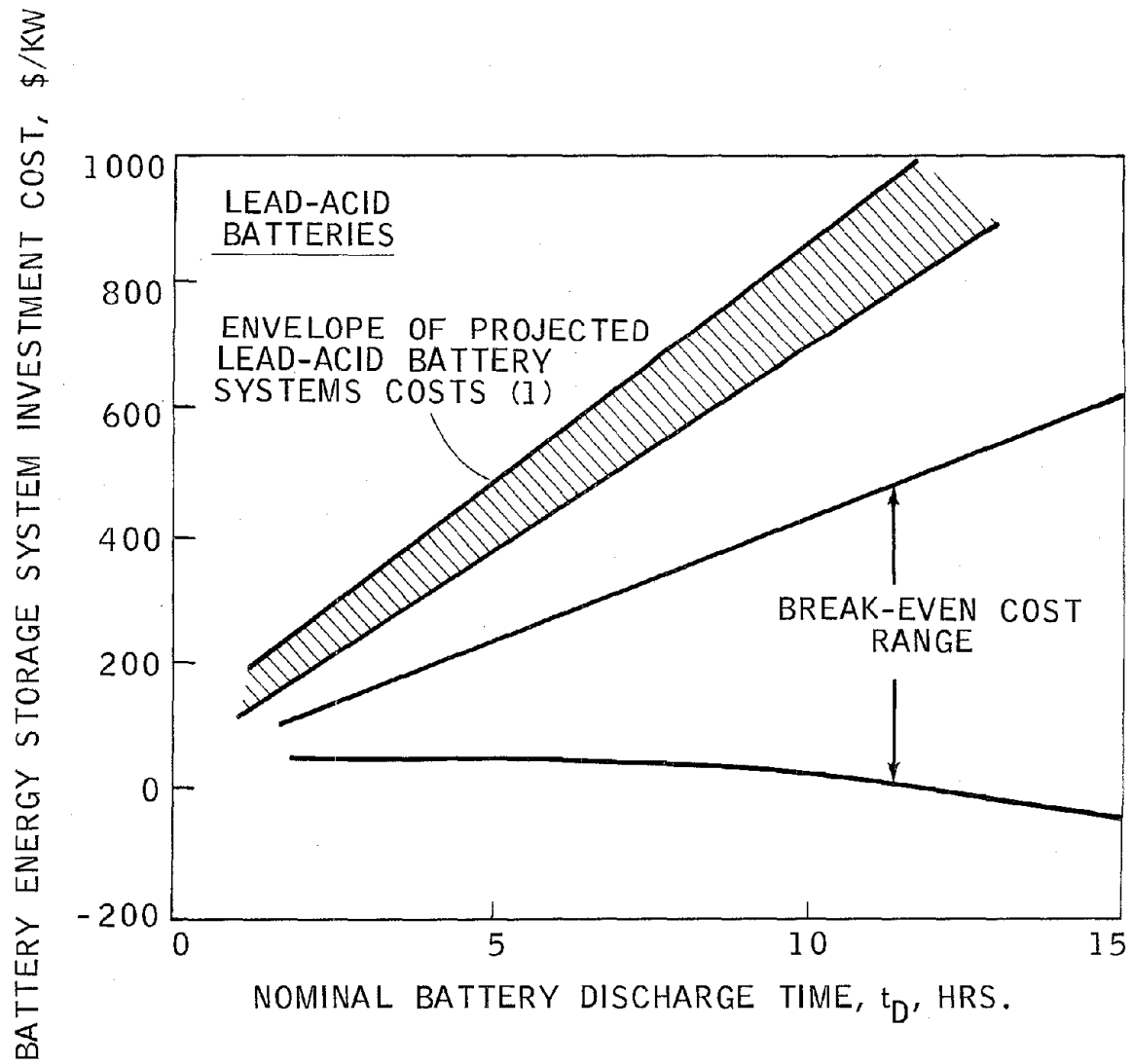
The projected costs for lead-acid and advanced battery systems are compared with their respective break-even cost target ranges in Figures 3-8 and 3-9. It can be seen that the expected cost of lead-acid battery systems is considerably higher than required. On the other hand, the advanced battery cost estimates appear quite attractive, but this may reflect optimistic projections for systems at an early stage of development.

The impact of facility life and turn-around energy storage efficiency on system cost targets were discussed in a previous section. In general, advanced batteries will be required to have useful lives approaching 20 years. Turn-around efficiencies between 70 and 80 percent should be adequate.

Finally, additional effort will be required to define the operating and maintenance (O and M) costs of electrochemical energy storage systems. At present, insufficient information is available on the operating characteristics for complete advanced battery systems. Thus, reliable O and M cost projections are not available.

Figure 3-8

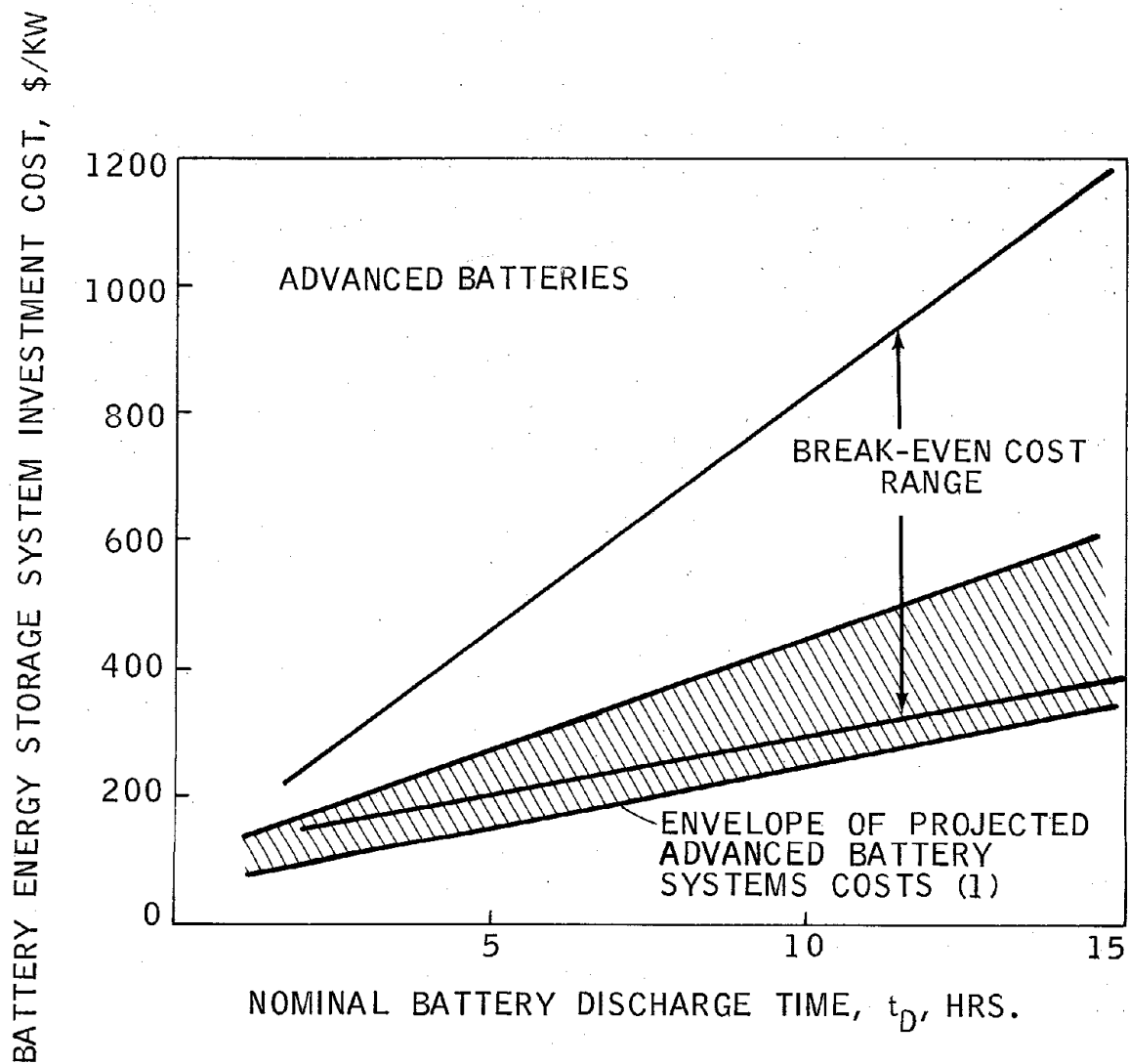
Comparison of Projected Investment Cost For Lead-Acid
Battery Systems With Break-Even Investment Costs



(1) Projected cost range calculated from: (50-100 \$/KW)
+ (65-77 \$/KWH) t_D

Figure 3-9

Comparison of Projected Investment Cost For Advanced
Battery Systems With Break-Even Investment Costs



(1) Projected cost range calculated from: (50-100 \$/KW)
+ (20-35 \$/KWH) t_D

3.2.4.4 Environmental and Safety Considerations

Energy storage systems could be located at various points in the utility network. Various economic credits can be projected for storage units in the distribution network, close to demand loads. But the cost of land, environmental factors, safety, maintenance requirements, etc. may dictate the location of the storage system at central station sites.

Battery energy storage systems have inefficiencies, in both the battery and the power conditioning equipment. These inefficiencies appear as heat. Even relatively small systems, 10-50 MW, could place a large thermal load on the environment. Large systems will require special provisions for cooling. Battery systems, such as sodium-sulfur and lithium-iron sulfide, will produce heat at elevated temperatures and require different cooling methods than lead-acid systems, which produce their heat at near ambient temperatures.

If cooling is provided by circulating air over and through stacks of batteries, fumes and vapors could be released to the environment in normal operation. In the event of a catastrophic failure, hazardous chemicals could be released to the environment. Oxygen from the air could react with the battery materials (e.g., sodium or lithium) and cause fires. Secondary coolant loops may be required, with heat exchange to cooling air or water. For example, it has been proposed that alkali metal, high temperature battery rooms be filled with argon, since the hot alkali metals will react with nitrogen. While this reduces hazards, it introduces maintenance problems.

If secondary coolant loops are not used, provisions would have to be made to scrub the coolant air. The scrubbers would have to be sized to handle the catastrophic failures. The volume and, to a lesser extent, the weight of the battery system, enters into the site selection. While the volume is important, the physical spacing of strings of batteries, the access for maintenance, cooling loops, etc., will determine the land area for the site. The area needed will probably be similar for all battery systems. The Redox system, which at first glance has a volume density less than lead-acid for active components, is probably more compact in final form than other systems. Battery buildings may be required for temperature control or hazard contaminant control. This will probably not be true for the nickel-hydrogen, zinc-air and Redox systems. However, Redox systems may use large volumes of potentially hazardous supporting electrolytes, such as hydrochloric or sulfuric acids.

Lastly, noise emissions must be considered for energy storage systems, particularly those located close to urban load centers. Typical current noise limits on utility installations are set at about 48 db, at the property line.

Noise sources for battery energy storage systems include power conditioning equipment, cooling air, pumps and reaction air (for zinc-air batteries). Power conditioning equipment could be designed to meet the noise level requirements. Cooling air requirements could be quite large for some systems, particularly low temperature, inefficient batteries. Well-designed blower installations will be required for these systems. Liquids pumps will probably not contribute significantly to noise levels. The zinc-air system would require an air flowrate of about 10^6 CFH for a 10 MW system. Larger systems would appropriately scaled. Again, air blowers would have to be appropriately designed to minimize noise emissions.

Summing up, it appears that available candidate electrochemical systems can meet the technical and environmental requirements for bulk energy storage in electric utilities, but at variable cost. Ultimately, the cost factors will predominate.

3.3 Task III Studies - Redox Battery Model Development and Systems Analysis

In Task III of this program, mathematical models of Redox battery energy storage systems were developed and programmed for use with high speed electronic computers. The models, labeled Stages 1, 1.5 and 2, are of increasing complexity and sophistication. These models were then used to carry out a techno-economic systems analysis of the Redox battery concept for the full range of peaking and intermediate duty energy storage applications in daily and weekly cycles, as defined earlier. In their present state, the models are useful for scoping feasibility studies of Redox systems aimed at uncovering basic characteristics and limitations. In turn, these analyses can serve to identify potential problem areas to be emphasized in on-going and future R and D studies of the Redox battery.

3.3.1 Stage 1 Model Development

The Stage 1 Model is a relatively simple characterization of the Redox battery system, using time-averaged values for key operating parameters, including charging and discharging utility grid power levels and electrochemical performance factors. The basic outline of the Stage 1 Model was provided by NASA. Suitable sub-routines were added to size and cost the required auxiliary sub-systems comprising the complete, installed Redox storage facility. Detailed descriptions of the calculation procedures used, including computer program software items, are given in the Stage 1 Model documentation package, found in Volume 2 of this report. The Stage 1 Model program was developed using Fortran IV language and an IBM 370/168 computer. The program software is also compatible with the Univac 1106 computer available at the NASA Lewis Research Center. Copies of the completed program tape may be obtained from the NASA Program Manager. The documentation in Volume 2 does not include a program listing.

The following discussion is a brief review of the Stage 1 Model highlights. The items discussed include the overall process flowplan, specific subsection design philosophy, cost estimating details and comments on the limitations of the Stage 1 Model. The reader is urged to consult the Stage 1 Model documentation package in Volume 2 for further information.

3.3.1.1 Redox System Flow Plan and Components

A representative Redox system plot plan was selected to serve as a basis for sizing and costing the required plant sub-systems. The plot plan, shown in Figure 3-10, includes the following sections:

- + Redox converter section, including assembled Redox flow cells and bus-bars.
- + Tankage sections, including associated system manifold and piping.
- + Pump section
- + Filter section
- + Heat exchanger (cooler) section
- + Power conditioning section

• Redox Cell, Stack and Trailers

A parallel rib, bipolar electrode cell configuration, typical of current electrochemical industry practice, was selected for inclusion in the model. The cell configuration is shown in Figure 3-11. Individual cells are assembled into stacks using filter-press technology. The cells are connected in series, electrically, with the number of cells in a stack calculated to yield the desired stack charging voltage, regardless of possible shuntage current problems. Suitable end plates are used to constrain the assembled stack. These stacks are then assembled into shippable trailers for delivery and installation. To simplify the logic, fractional sections of stacks are allowed within individual trailers, and fractional trailers are allowed as part of the final installed storage facility. The latter permits exact delivery of the imposed voltage and power demands. Costs are developed for the stack components on the basis of adjusted material costs, and for the assembled trailer, including estimated bus-bar costs. Materials costs are selected by the program user. It is assumed that noble metal catalysts are not used. An installation cost estimate is also included.

• Tankage and Manifold Piping

The tankage section includes provision for storing the reactant solution inventory. The use of PVC-lined, carbon steel tanks is assumed, compatible with the expected use of corrosive supporting electrolytes, such as hydrochloric acid (18, 38). Costs were estimated for individual tanks ranging in capacity from 1000 to 500,000 bbl. The latter represent a considerable

Figure 3-10

Base-Line Plot Plan For Redox Storage System

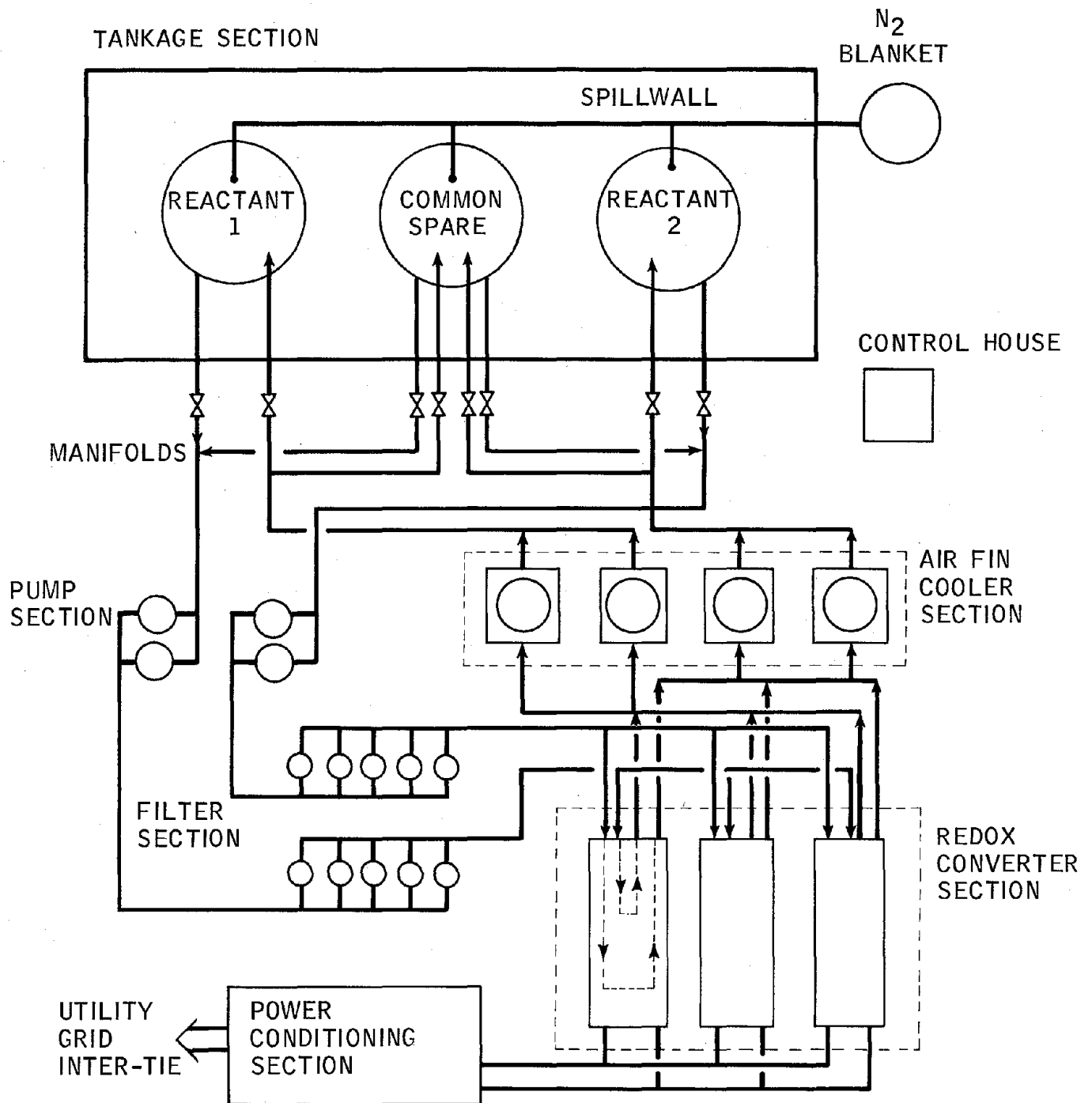
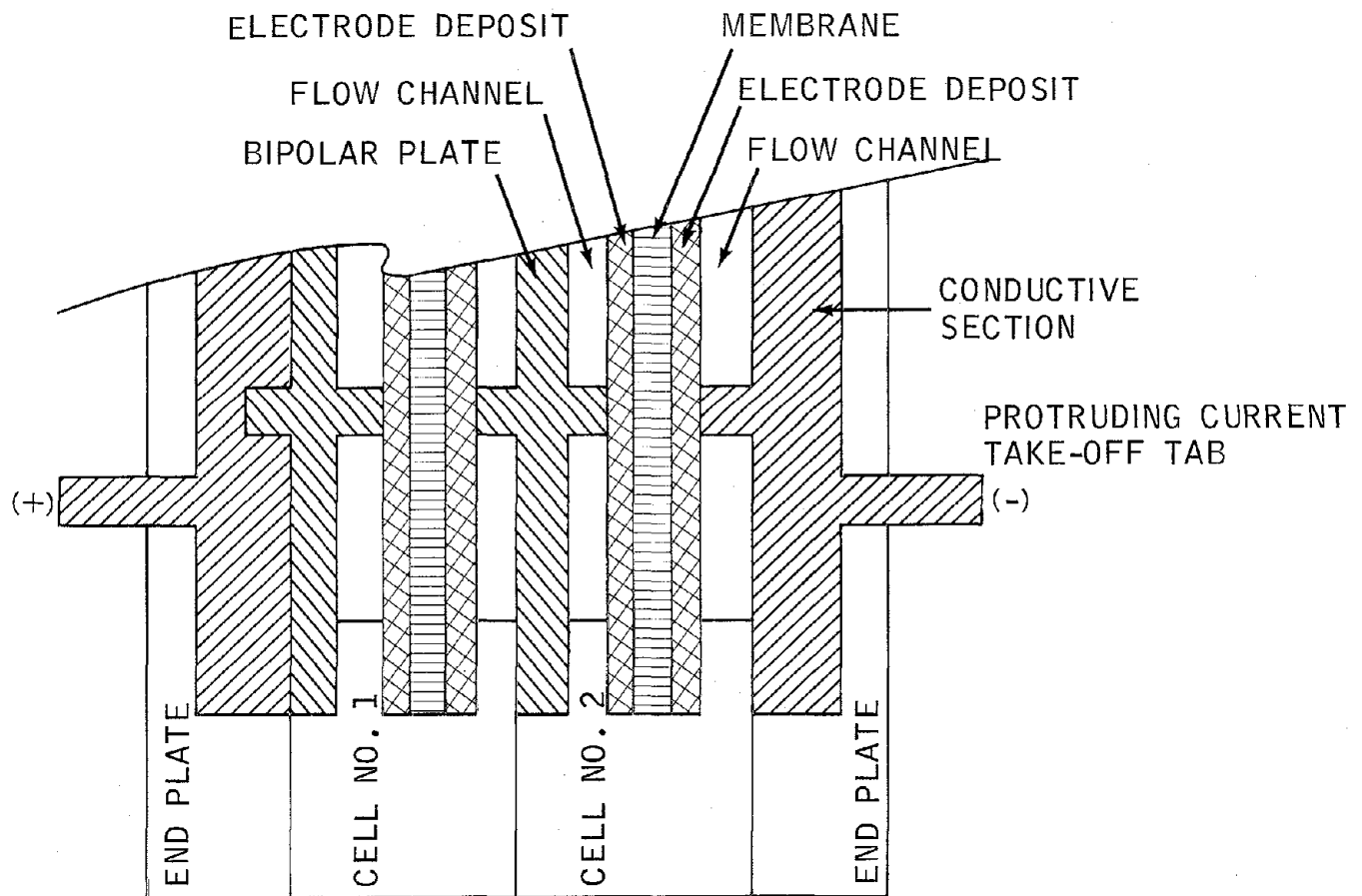


Figure 3-11

Schematic Cell Design for Stage 1 Model



TOP VIEW OF SLICE THRU CENTER

extrapolation from current industry practice. The tankage section includes a spare tank, used as a hold-tank during routine maintenance or emergency upsets on the active, working tanks.

Associated system manifold and piping were estimated by carrying out an initial, rough pressure balance. An allowable piping pressure drop was calculated, based on estimated or assumed pressure drops for the filters, Redox cells, heat exchangers and storage tank height. The system plot plan, shown in Figure 3-10, was used to estimate the length and number of fittings in the system. Cost estimates were made for PVC-lined carbon steel pipe and Hastelloy fittings, ranging from 4 to 18 inch diameter. Subsequent analysis showed that the piping costs were relatively small and that a complete pressure balance and line sizing procedure could not be included conveniently in the Stage 1 Model. Therefore, the piping and manifolding costs were included as part of the tankage section costs, assuming that smaller size pipe would be associated with small tanks, etc. The final tank section cost centers are listed below:

- + Tanks (delivered and erected)
- + PVC lining for tanks and spill walls
- + Mixers, including labor
- + Tank foundations, including labor
- + Materials and labor for other items: spill walls, manifolds, total system piping and pipe lining (PVC), tank insulation and tank painting.

- Pumps

Centrifugal pumps with Hastelloy casing and internals were assumed. A two pump system is used for each reactant, with each pump rated at 60 percent of full system capacity. A separate sparing philosophy was developed for flow rates exceeding the maximum assumed pump capacity of 6200 gpm. The maximum discharge pressure associated with the pumps is about 300-600 psig, depending on size. Pump drivers are also included, so that an estimate can be made of parasitic power consumption. Costs were developed for pump assemblies including driver motor controls and foundations.

- Filters

The filter section contains a number of parallel-manifolded cartridge filter assemblies, each consisting of several filters in a simple housing, based on vendor discussions. The maximum flow rate capacity of each assembly was estimated at 275 gpm. Subsequent analysis showed this approach to be quite costly. Further discussion of the filter problem is given in Section 3.3.4.

- Heat Exchangers (Coolers)

A heat balance was incorporated into the Stage 1 Model, using heat generation terms supplied by NASA. The heat duty on the exchanger system is equal to the total heat generated in the Redox converter cells. It is assumed that the Redox reactant streams leave the cells at the desired (assumed) cell operating temperature. These streams are cooled to a lower temperature for adiabatic storage in the tank system. This temperature is then considered to be the subsequent inlet temperature to the cells. In effect, the circulating Redox streams swing in temperature between T_{cell} and T_{storage} . Duty requirements are calculated for charge and discharge operation, and the maximum value is selected for sizing the exchangers. Modular, closed-loop air-fin exchangers are assumed, using Hastelloy tubes. The calculation procedure also estimates the blower horsepower required, and the costs. Exchanger costs were developed for systems rated at 2,20 and 200 M BTU/hr for interpolative costing routines.

- Power Conditioning

Estimates of the required power conditioning equipment size and cost were made using data from a recent study by Westinghouse (39). As a basis, the maximum operating power level was used to size the power conditioner. This power level could be the input ac power to the system during charging, or the output dc power from the system during discharge. For costing purposes, the voltage level associated with the maximum power level was selected. This is an important factor because the cost of the power conditioner increases from about 80\$/kw at 1000v to 150\$/kw at 200 volts. These costs are for a current-fed, naturally commutated inverter system, which was selected on the basis of general low cost and constant operating efficiency over a wide load range.

- Cost Estimation Approach

Simplified cost estimating procedures were used in the Stage 1 Model, consistent with the level of detail and sophistication employed to calculate the system performance characteristics. Costs are estimated for each process section, using the bases described above and in the documentation package. Generally, these estimates are made by interpolation from cost curves that were derived from cost estimates made for individual test cases that covered a broad range of equipment size. Associated piping and manifolding requirements are factored into the overall section equipment cost. The process section equipment costs (tankage, pumps, filters and coolers) have been reported as total installed costs, on a 1Q76 basis (instantaneous costs). Materials and equipment are assumed purchased on the Gulf Coast, with installation in the S.E. USA.

In general, indirect costs include detailed engineering at 5%, erection fees at 2% and basic engineering at 2% of direct materials costs. The tanks and tank linings are assumed to be subcontracted items, involving the basic engineering charge only. Preliminary analysis showed that the process section installation was not labor intensive. That is, labor costs were a small fraction of total direct costs. A 20% project contingency is applied, to account for unexpected site-specific factors. The costs of land and site improvement are not included, since it was assumed that the Redox system is installed at existing utility facilities.

The costing approach for the Redox converter and power conditioning sections is somewhat different. Direct equipment costs are calculated in a straight-forward manner. Then, suitable cost factors, generally expressed on a \$/kw of power basis, are used to estimate the total installed cost. This factor approach has proved useful in other studies of large utility - scale electrochemical systems. Finally, the solution inventory costs are calculated, including both reactants and supporting electrolytes on the basis of assumed delivered costs.

The Stage 1 Model costing routines thus provide an estimate of the total installed capital investment cost. Attempts to estimate associated operating and maintenance costs were not made, due to lack of information on specific O and M requirements for candidate Redox battery systems, e.g., specific Redox couple chemistry, etc.

3.3.1.2 Stage 1 Model Performance Characteristics and Output

Analysis of the Stage 1 Model revealed some interesting features. The Stage 1 Model logic permits the calculation of any one of the following daily cycle storage system characteristics, given the other three:

- + Time-averaged AC charging power (\mathcal{P}_C)
- + Charging time (t_C)
- + Time-averaged AC discharging power (\mathcal{P}_D)
- + Discharge time (t_D)

The model is energy-conservative, in that all charged (stored) energy is required to be discharged in the indicated discharge time. This is accomplished by suitable adjustment of the Redox cell current density during discharge. Thus, for a fixed charge time (and a fixed charge power level), the discharge power level decreases as discharge time is increased. This results in operation at lower discharge current density, where voltage losses are lower. In turn, the overall storage system turn-around efficiency increases.

In an analogous manner, if the discharge time (and charge power) are held constant, then the discharge power level increases as the charge time (hence energy stored) increases. An exception to this occurs when the charge time is long and the discharge time is relatively short. Here, the model calculates a high discharge current in order to fully discharge the stored energy in the required time span. The model selects a value of discharge

current density that results in operation well beyond the peak power out-put of the system, an undesirable feature.

Algebraic analysis of the Stage 1 Model also showed that the main system inputs ρ_D , ρ_C , t_C and t_D are related in a straightforward manner, using the nomenclature provided by NASA and described in the documentation package:

$$\rho_D = \alpha_1 \frac{t_C}{t_D} \rho_C \left(\alpha_2 - \alpha_3 \frac{t_C}{t_D} \right) \quad (1a)$$

where:

$$\alpha_1 = \frac{E_R E_{fC} E_{fD} E_I}{v_R + i_C \delta + a_C + b_C i_C} = \frac{E_R E_{fC} E_{fD} E_I}{v_C}$$

$$\alpha_2 = v_R - a_D$$

$$\alpha_3 = E_{fC} E_{fD} i_C (b_D + \delta \rho)$$

or:

$$v_D = \left(\alpha_2 - \alpha_3 \frac{t_C}{t_D} \right)$$

Therefore:

$$\rho_D = E_R E_{fC} E_{fD} E_I \left(\frac{\rho_C t_C}{t_D} \right) \left(\frac{v_D}{v_C} \right) \quad (1b)$$

Note that Equations (1a) and (1b) are equivalent. Equation (1a) contains only those parameters specified prior to the use of the Stage 1 Model program. Further algebraic manipulation yields:

$$\rho_C = \frac{\rho_D}{\left(\alpha_1 \frac{t_C}{t_D} \right) \left(\alpha_2 - \alpha_3 \frac{t_C}{t_D} \right)} \quad (2)$$

$$t_C = \frac{\alpha_2 t_D}{2\alpha_3} \left[1 - \sqrt{1 - \frac{4\alpha_3 \rho_D}{\alpha_1 \alpha_2^2 \rho_C}} \right] \quad (3)$$

$$t_D = \frac{\alpha_1 \alpha_2 \rho_C t_C}{2\rho_D} \left[1 + \sqrt{1 - \frac{4\alpha_3 \rho_D}{\alpha_1 \alpha_2^2 \rho_C}} \right] \quad (4)$$

Equations (1a) and (2-4) are used to determine the missing parameters, given initial values for three of the following: ϕ_D , ϕ_C , t_D , t_C .

It can also be shown that the maximum discharge power level, $\phi_{D\text{MAX}}$, is calculable:

$$\phi_{D\text{MAX}} = \frac{\alpha_1 \alpha_2 \phi_C^2}{4\alpha_3} \quad (5)$$

The energy storage efficiency at $\phi_{D\text{MAX}}$, $\gamma_{\phi_{D\text{MAX}}}$, also can be calculated

$$\gamma_{\phi_{D\text{MAX}}} = 1/2 \alpha_1 \alpha_2 \quad (6)$$

where the efficiency has its usual definition neglecting power consumed by the system auxiliaries:

$$\gamma = \frac{\phi_D t_D}{\phi_C t_C}$$

Lastly, the maximum possible efficiency can be estimated:

$$\gamma_{\text{MAX}} = \alpha_1 \alpha_2 = 2 \gamma_{\phi_{D\text{MAX}}} \quad (7)$$

These algebraic expression can be used for pre-analysis of prospective Stage 1 Model parameters.

The completed Stage 1 Model contains 65 parameters whose values are user-specified as input data. These parameters include electrochemical performance, system design and component cost factors. The input data display is discussed in the documentation package. A sample printout of the Stage 1 Model output package is given in Table 3-20.

3.3.1.3 Stage 1 Model Limitations

The Stage 1 Model provides an adequate basis for preliminary scoping studies of the Redox energy storage system. However, some critical features of Redox battery operation are lacking in the model. The possible deficiencies of the Stage 1 Model include:

- + Model logic is restricted to analysis of daily cycles.
- + System sizing is based on time-averaged quantities.
- + No consideration is given to the shape of the charge/discharge cycle.
- + No consideration is given to factors associated with multi-cycle operation, e.g., component lifetimes, operating and maintenance costs, solution regeneration, cycle to cycle variations in charging or discharge profiles.
- + No consideration is given to overcharge and overdischarge.
- + No consideration is given to flow-electrochemical performance interrelationships, total system pressure balance or shuntage current losses.

Table 3-20

Sample Printout from Stage 1 Model

CASE 2-1
SENSITIVITY ANALYSIS

DATA OF SEPT. 2, 1976

RUN SEPT. 7, 1976

CHARGE	DESCRIPTION	DISCHARGE	UNITS
TC	5.000 TIME	4.000 TD	HOURS
SCRPC	21.965 TIME AVERAGED AC POWER	20.000 SCRPD	MW
CAPPC	20.866 CONVERTER POWER	21.053 CAPPD	MW
CAPIC	41.733 CONVERTER CURRENT	52.114 CAPID	KAMPS
IC	0.100 CELL CURRENT DENSITY	0.125 ID	AMP/CM2
ER	0.950 RECTIFYING/INVERSION EFF.	0.950 EI	-
CAPVC	500.000 CONVERTER VOLTAGE	403.975 CAPVD	VOLTS
AL	0.0 NON-OHMIC COEF.--INTERCEPT	0.0 AD	VOLTS
BC	0.500 NON-OHMIC COEF.--SLOPE	0.500 BD	V.CM2/AMP
DELVC	0.050 NON-OHMIC CELL POLARIZATION	0.062 DELVD	VOLTS
VC	0.875 CELL VOLTAGE	0.706 VD	VOLTS
PC	0.087 POWER DENSITY	0.088 PD	W/CM2
QC	1.789 WASTE HEAT	-2.795 QD	MW
S1C	0.247 GENERATION / CONSUMPTION	0.309 S1D	KMOLS/SEC
S2C	0.247 OF SPECIES 1 AND 2	0.309 S2D	KMOLS/SEC
W1C	0.247 REACTANT FLOW, SPECIES 1	0.309 W1D	KMOLS/SEC
W2C	0.247 REACTANT FLOW, SPECIES 2	0.309 W2D	KMOLS/SEC
F1C	1.000 SOLUTION FLOW/CELL, SPECIES 1	1.000 F1D	-
F2C	1.000 SOLUTION FLOW/CELL, SPECIES 2	1.000 F2D	-

CELL DATA

TOTAL CELL AREA	23847.223	CAPA	M2
NUMBER OF SERIES CELLS ...	572.	NS	-
NUMBER OF PARALLEL CELLS..	261.	NP	-
TOTAL NUMBER OF CELLS	149292.	CAPN	-
AREA PER CELL	1597.354	AXA	CM2
THERMAL EFF.	1.000	ET	-
FARADAIC EFF. (CHARGE)....	1.000	EFC	-
FARADAIC EFF. (DISCHARGE)..	1.000	EFD	-
CELL VOLTAGE	0.800	VR	VOLTS
MEMBRANE THICKNESS	0.0100	DELTA	CM
SPECIFIC RESISTIVITY	25.000	RHO	OHM.CM

SPECIE DATA

	SPECIE 1	SPECIE 2	
MOLECULAR WEIGHT	150.000 MW1	150.000 MW2	-
MOLES INVOLVED IN CHARGE	4448.781 M1	4448.781 M2	KMOLS
ELECTRONS TRANSFERRED ..	1. Z1	1. Z2	EQ/MOL
TOTAL REACTANTS REQUIRED	4448.781 SCRMI	4448.781 SCRMI	KMOLS
VOLUME OF SOLUTION	4448.781 CAPV1	4448.781 CAPV2	KLITRES
REACTANT CONC.	1.000 C1	1.000 C2	MOLS/L
ELECTROLYTE CONC.	5.000 C1S	5.000 C2S	MOLS/L
REACTANT UTILIZATION ...	1.000 U		-
MOLES OF ELECTROLYTE ...	44487.812 MS		KMOLS

CASE 2-1
SENSITIVITY ANALYSIS
DATA OF SEPT. 2, 1976 RUN SEPT. 7, 1976

INVESTMENT COSTS
(THOUSAND \$)

FUNCTIONAL SECTION	INSTALLED COST
-----------------------	-------------------

TANKAGE	2010.
PUMPS	535.
FILTERS	8153.
COOLERS	2429.
TRAILERS	4166.
POWER CONDITIONING	2694.

TOTAL EQUIPMENT COST	19987.

SOLUTION COSTS

REACTANT 1	350.
REACTANT 2	350.
ELECTROLYTE	204.

TOTAL CHEMICAL COST	904.
---------------------	------

TOTAL INSTALLED INVESTMENT COST	20891.
---------------------------------	--------

INVESTMENT COST	1045. \$/KW
(BASED ON DISCHARGE OPERATIONS)	261. \$/KWH

CASE 2-1
 SENSITIVITY ANALYSIS

DATA OF SEPT. 2, 1976

RUN SEPT. 7, 1976

POWER GENERATION
 (MEGAWATTS)

	CHARGE	DISCHARGE
GROSS POWER GENERATED	21.96	20.00
AUXILIARY POWER CONSUMED		
PUMPS	0.71	0.71
TANKS	0.02	0.02
COOLERS	0.04	0.04
TOTAL	0.76	0.76
NET POWER DELIVERED	22.73	19.24

-----ENERGY STORAGE EFFICIENCY-----

EXCLUDING AUXILIARY POWER CONSUMPTION	(%)	72.84
INCLUDING AUXILIARY POWER CONSUMPTION	(%)	67.72

-----STAGE 1 MODEL LIMITING CONDITIONS-----

MAXIMUM DISCHARGE POWER	(MW)	48.33
EFFICIENCY AT MAXIMUM POWER	(%)	41.26

P O W E R C O N D I T I O N I N G

SYSTEM MAXIMUM POWER	(MW)	21.96	CHARGE
SYSTEM MAX VOLTAGE	(VOLTS)	500.00	CHARGE
COST RATE	(\$/KW)	102.65	
EQUIPMENT COST	(K\$)	2254.72	
COST, INSTALLED	(K\$)	2694.	

- 65 -
Table 3-20 (Cont'd)

CASE 2-1
 SENSITIVITY ANALYSIS

DATA OF SEPT. 2, 1976

RUN SEPT. 7, 1976

EQUIPMENT DETAILS

REACTANT 1 REACTANT 2 COMMON SPARE

TANK DATA

		REACTANT 1	REACTANT 2	COMMON SPARE
SIZE	(BBL)	32551.	32551.	32551.
NUMBER OF TANKS		1.	1.	1.
MIXER	(HP)	11.	11.	11.
COST, INSTALLED	(K\$)	670.	670.	670.

PUMP DATA

SYSTEM FLOW RATE	(GPM)	4932.	4932.
NUMBER OF PUMPS		3.	3.
PUMP SIZE	(GPM)	2466.	2466.
MOTOR POWER	(HP)	237.	237.
COST, INSTALLED	(K\$)	268.	268.

COOLER DATA

SYSTEM FLOW RATE	(GPM)	4932.	4932.
DUTY	(MEGA BTU/HR)	4.76	4.76
PLOT AREA	(FT ²)	271.	271.
DESIGN CONDITION:		DISCHARGE	DISCHARGE
FAN POWER	(HP)	25.	25.
COST, INSTALLED	(K\$)	1215.	1215.

OUTLET TEMP	(DEG.C)	
CHARGE		51.03
DISCHARGE		48.71

FILTER DATA

SYSTEM FLOW RATE	(GPM)	4932.	4932.
NUMBER OF FILTERS		17.93	17.93
FILTER SIZE	(GPM)	275.	275.
COST, INSTALLED	(K\$)	4077.	4077.

- 66 -
Table 3-20 (Cont'd)

CASE 2-1
SENSITIVITY ANALYSIS

DATA OF SEPT. 2, 1976 RUN SEPT. 7, 1976

EQUIPMENT DETAILS

CELL / STACK DATA

POWER RATINGS:		CHARGE	DISCHARGE
CELL POWER DENS. (MILLIWATTS/CM2)		87.50	88.28
STACK POWER (KW)		79.95	80.66
TRAILER POWER (MW)		1.34	1.35
CELL DATA:			
SIZE (CM)		39.97	
AREA (CM2)		1597.35	
THICKNESS (CM)		0.73	
MEMBRANE AREA (CM2)		1757.09	
PLASTIC VOLUME (CM3)		1018.79	
CURRENT COLLECTOR VOLUME (CM3)		1080.61	
ELECTRODE DEPOSIT (GM)		17.57	
CELL MATERIAL COST (\$)		8.56	
NUMBER OF CELLS IN STACK		572.	
TOTAL CELL COST (K\$)			4.89
END PLATE:			
THICKNESS (CM)		2.50	
PLASTIC VOLUME (CM3)		10286.87	
CONDUCTIVE MAT'L VOLUME (CM3)		5750.87	
NUMBER OF END PLATES IN STACK		2.	
TOTAL MATERIAL COST FOR STACK END PLATES (K\$)			0.03
TOTAL STACK MATERIAL COST (K\$)			4.92
STACK MANUFACTURED COST (K\$)			12.34
STACK SIZING:			
BARE LENGTH (CM)		423.	
BAKE WIDTH (CM)		55.95	
BARE HEIGHT (CM)		55.95	
VOLUME INSTALLED (M3)		5.37	
TRAILER VOLUME (M3)		90.	
STACKS / TRAILER		16.73	
CELLS / TRAILER		9567.	
NUMBER OF TRAILERS		15.60	
SINGLE TRAILER COST (K\$)			240.
SINGLE TRAILER INSTL'D COST (K\$)			267.
TOTAL TRAILER COST, INSTALLED (K\$)			4166.

The program user must "assume" quantities which are not, in reality, independent variables. These quantities include the form and coefficients of an expression for non-ohmic cell polarization, which actually depends on cell temperature, cell design, flow rates and local reactant concentrations within the cell. In effect, the specific characteristics peculiar to the Redox cell concept have been neglected in the model.

The use of time-averaged quantities is a considerable oversimplification. Redox cell performance critically depends on the concentration level of reactants and the achievable reactant conversion levels that can be obtained in cell operation. Reactant utilization factors, concentrations and charge and discharge rates cannot, in fact, be assigned independently.

Redox cell operation involves a considerable interaction between hydrodynamic and electrochemical factors. It is expected that Redox couples with high exchange current density will be selected. This means that activation polarization losses will be small. Major sources of voltage loss will be confined to concentration polarization and ion-resistance losses. In turn, concentration polarization critically depends on the hydrodynamic environment established within the flowing electrolyte Redox cell.

These possible deficiencies were recognized at the beginning of the study program. More sophisticated models of the Redox battery were developed to overcome them.

3.3.2 Stage 1.5 Model Development

As indicated above, the Stage 1 Model logic is limited to the analysis of daily energy storage cycles. Therefore, an intermediate Stage 1.5 Model was developed to permit the analysis of promising weekly storage cycles. The Stage 1.5 Model is a simple extension of the Stage 1 Model, modified to include a variable reactant inventory. The Stage 1.5 Model is still constrained to single values of the discharge and charge power levels, but these levels can now be imposed for varying times in a weekly pattern. An optimization feature was added, allowing a search for a value of the charging current density that yields a minimum system investment cost. The basic electrochemical performance and system design and cost characteristics remain unchanged. The Stage 1.5 Model is described in detail in a separate documentation package, found in Volume 2 of this report.

3.3.3 Stage 2 Model Development

The Stage 2 Model is an expanded version of the Stage 1 and 1.5 Models, designed to overcome the disadvantages of these simple models, particularly in the area of load-following capability and electrochemical performance-hydrodynamic interactions. The Stage 2 Model can process a user-supplied profile of discharge power and time requirements and charge power and time availability. Power profile variation is permitted over any time interval. Thus, the model is able to handle a wide range of potential utility operation.

The Stage 2 Model is limited to simulation. The user specifies an initial system estimate of reactant inventory and number of Redox converter trailers. The model carries out system operation as demanded, using the logic described below. Successfully completed cycles are sized and costed, using the Stage 1 Model approach. Output signals are provided to guide the user if the required cycle requirements cannot be attained. Examples here include insufficient reactant supply and/or insufficient number of Redox converter trailers.

The model does not contain internal optimization routines to search for minimum cost combinations of reactant inventory and number of trailers. In effect, the user carries out the optimization search by parametric variation of key input variables.

The following discussion is a brief review of important features of the Stage 2 Model. Detailed description of the model software is presented in the documentation package found in Volume 2. Design equations, logic diagrams and operating experience are included.

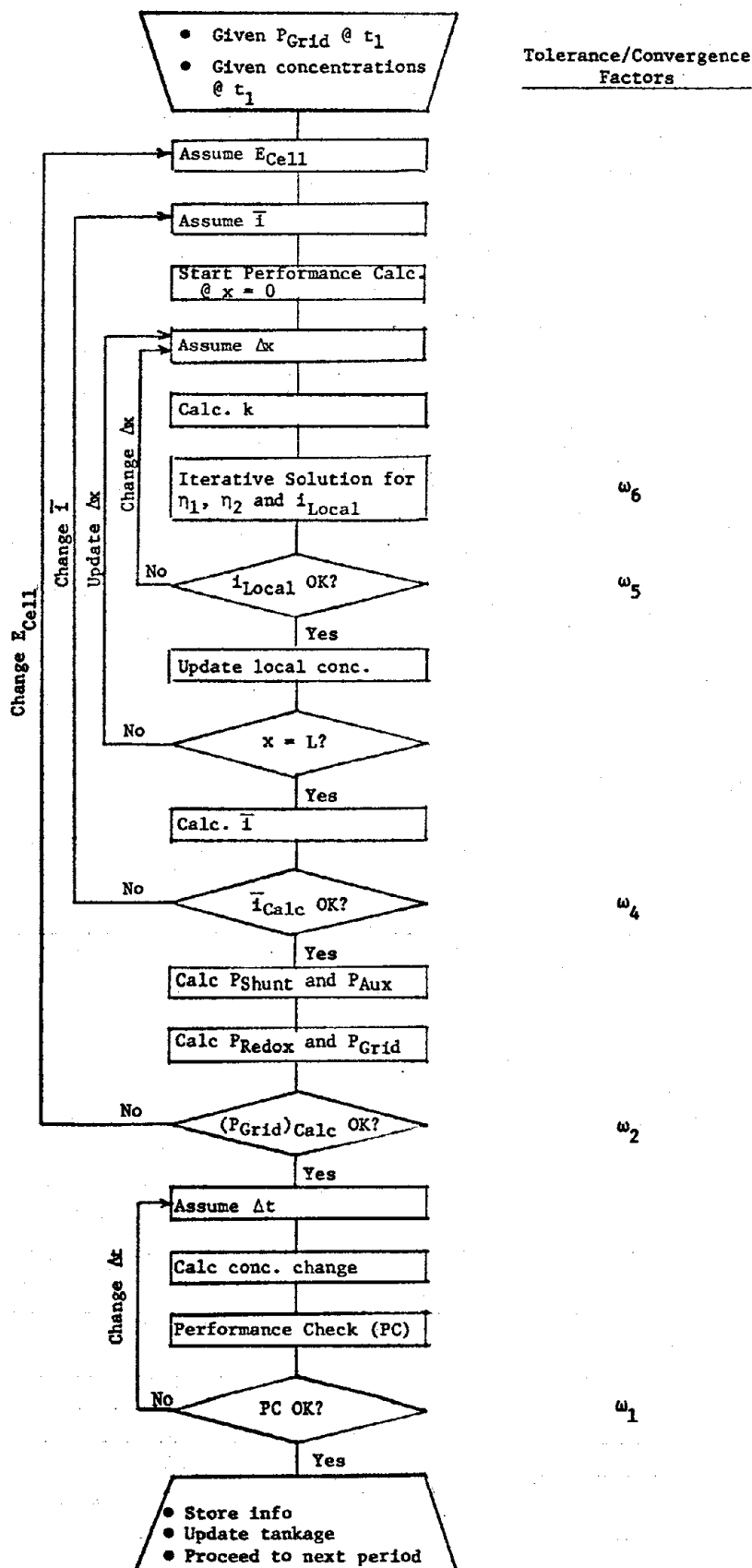
3.3.3.1 Stage 2 Model Logic

The Stage 2 Model features a load-following capability. At any time, t , the model attempts to match the required grid power level (discharge or charge), using instantaneous values for reactant composition. A nested series of logic loops is used, shown in Figure 3-12, including:

- + Assumed value of time increment, Δt
- + Assumed value of cell voltage, E_c
- + Assumed value of average cell current density, \bar{i}
- + Assumed value of path length increment through the Redox cell, Δx
- + Assumed value of local current density required to satisfy electrochemical and mass transfer performance, i_{local} .

Figure 3-12

Simplified Logic Sequence for Redox
System Performance Evaluation



Evaluation of shuntage current losses, heating effects and flow rates are included at appropriate places within the loops. Initial estimate routines are provided for the assumed parameter values to speed convergence. Tolerance testing is provided, with tolerance limits set by the user. This approach was used to provide a maximum opportunity for the user to modify the program in an intelligent manner, as experience and learning occur during subsequent program operation.

The performance calculation proceeds for a time increment, Δt , such that the variation in cell performance caused by changes in input reactant concentration is within a prescribed tolerance, or until P_{grid} changes. A well-mixed reactant tankage system is assumed, with logic to handle multiple tank arrays.

3.3.3.2 Redox Cell, Stack and Trailer Design

An assumed cell and stack configuration was selected in order to carry out the design of the Redox converter section. A number of possibilities existed for each. For the individual cell design, the following bases were considered:

- + Fixed electrode, parallel plate filter-press construction versus fluidized bed electrode design.
- + For the fixed electrode case, bipolar or mono-polar construction can be assumed. In either case, a flow-by or flow-through electrolyte configuration can be used.
- + For the flow-by, bipolar designs, the electrode deposit can be placed on the bipolar plate or on the separating membrane.

The flow-by and flow-through designs are depicted in Figure 3-13, together with a brief listing of potential advantages and disadvantages. For the Stage 2 Model, a relatively simple design was chosen, involving:

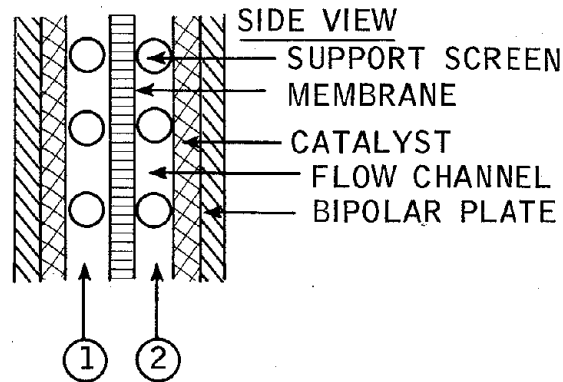
- + Fixed bipolar electrodes assembled in a parallel plate, filter-press configuration.
- + Flow-by electrodes with the catalyst deposit placed on the bipolar plate. A simple non-conducting woven screen insert would be used to brace the membrane and to provide eddy promotion to enhance local mass transport rates within the electrolyte flow chambers.

Figure 3-13

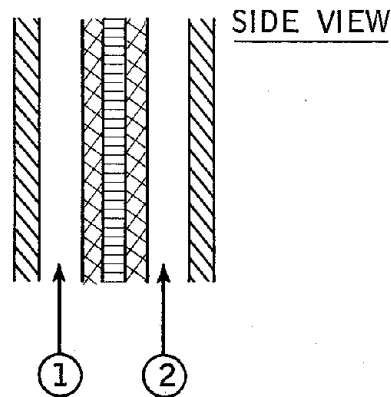
Cell Configuration Schemes

FLOW-BY ASSEMBLIES

CATALYST ON BIPOLAR PLATE

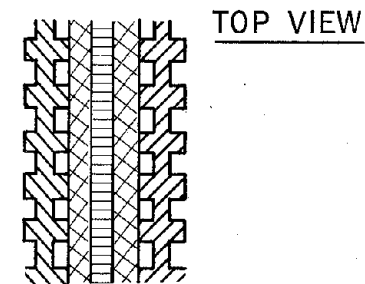


Simple Construction
No Current Connection Problem
Low ΔP
Membrane Exposed, Higher
Reactant Cross-Diffusion

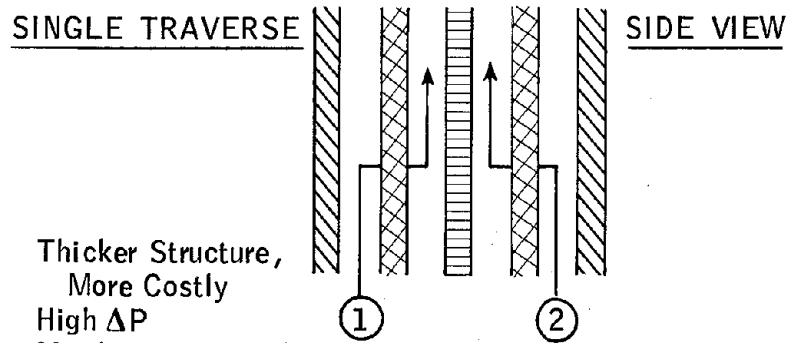


More Complex Construction
Current Connection Surface Blocks Catalyst
Current Flux Lines Distorted
Higher ΔP
Less Cross-Diffusion of Reactants thru Membrane

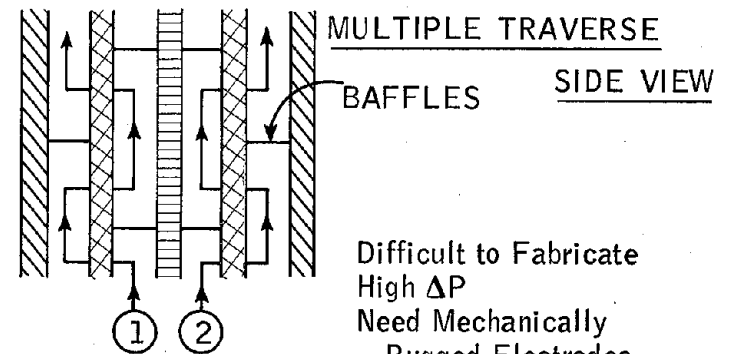
CATALYST ON MEMBRANE



FLOW-THROUGH ASSEMBLIES



Thicker Structure,
More Costly
High ΔP
Membrane Exposed,
Higher Cross-Diffusion
Uncertain Flow Distribution



Difficult to Fabricate
High ΔP
Need Mechanically
Rugged Electrodes

The constructional features of the parallel plate assembly are relatively well understood and are tractable, using modern fabrication techniques. The use of the bipolar plate configuration, with adjacent cells stacked electrically in series will eliminate current flow losses associated with the side-tab current draw-off required with mono-polar designs. Placing the catalyst deposit on the surface of the conducting bipolar plate will eliminate the problems associated with current collection and non-uniform current flux within the cell. This placement also eliminates the need for a conductive bracing structure to conduct electrons from the surface of the catalyst deposit to the bipolar plate. Typically, these structures can be parallel ribs or cylindrical protrusions on the surface of the bipolar plate. The parallel rib geometry, while used in electrochemical cell design, would complicate the analysis of internal cell mass transfer, as discussed below.

The flow-by configuration also was chosen, again on the basis of relative ease of analysis. No immediate operational advantages were seen for the flow-through design. On the other hand, the flow-through cells would be thicker and, therefore, more costly to construct.

Turning to the operation of the cells, a co-current flow assembly was selected, illustrated in Figure 13-14. Here, both reactants enter at the same edge of the cell and flow in parallel, maintaining a reasonably constant inter-compartment pressure drop across the membrane. In turn, this will reduce bulk electrolyte flow through the membrane. Again, this practical configuration was chosen for ease of analysis. The alternative counter-current flow and cross-flow systems are both complicated, requiring iterative calculations for mass-balance and current generation and give higher pressure drops across the membrane.

Lastly, the flow operation of the stack was considered. The filter-press assembly design could use entrance and exit manifolds that would couple the cells in parallel, hydraulically. As shown in Figure 13-15, the flow through the stack can be arranged as either "feed-forward" or "feed-backward," with a single pass through individual cells. The feed-forward form appears more attractive, based on a preliminary analysis of literature studies on flow distribution. An alternative, multiple-cell pass operation, also illustrated in Figure 13-15, was rejected as adding unjustified complexity and higher flow path pressure drops.

The assembled stacks are assumed to be factory-mounted in shippable trailer-sized packages, as in the Stage 1 Model.

Operationally, the user of the Stage 2 Model will specify the dimensions, assembly details and cost factors associated with the selected Redox designs, as described above. Internal dimension checks are carried out to ensure a consistent design. These procedures are fully described in the Stage 2 Model documentation package.

3.3.3.3 Redox Kinetics and Electrochemical Performance

A comprehensive analysis was carried out to define the effects on Redox cell performance of local variations in concentration-dependent reversible potential, activation and concentration polarization and ohmic losses. The approach used is essentially that of Bockris and co-workers (40,41).

Figure 3-14

Cell Flow Schemes

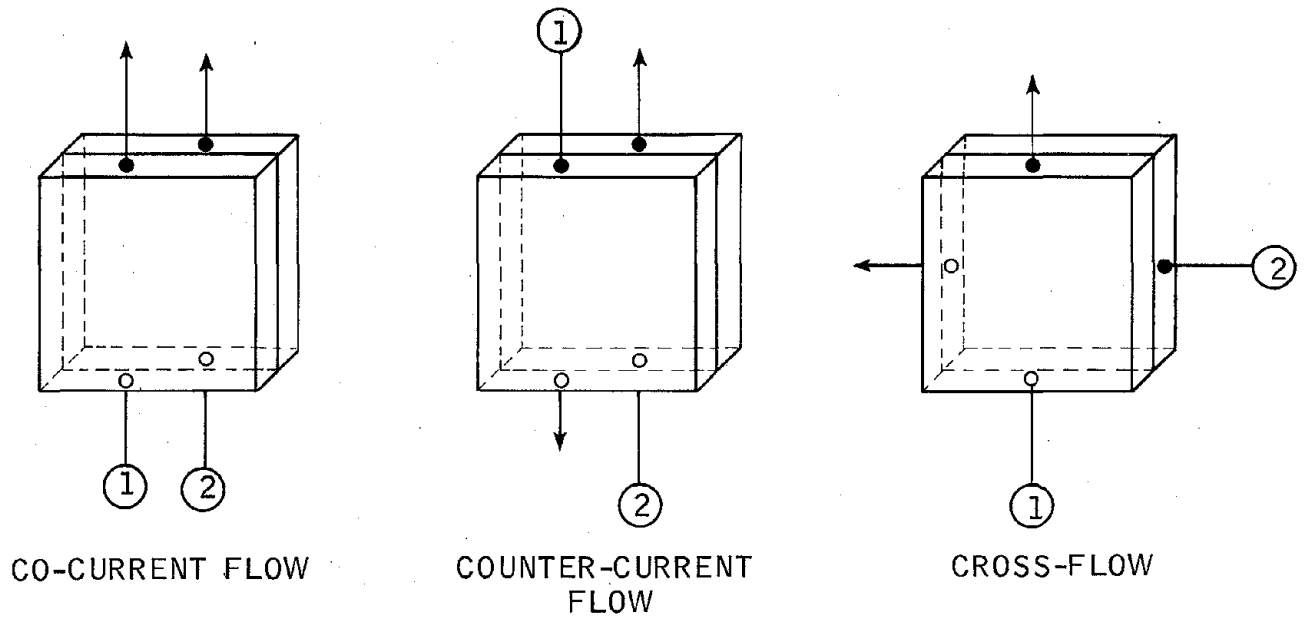
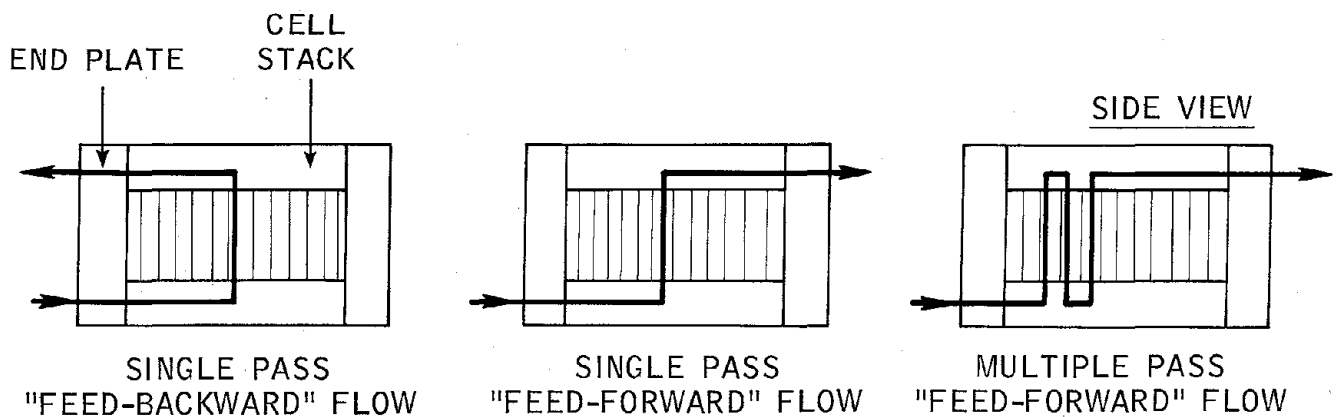


Figure 3-15

Stack Flow Schemes



The model assumes iso-potential electrode operation and derives the local potential balance, including a concentration-dependent form of the Butler-Volmer relation between current density and electrode over-potential. Surface and bulk reactant and product concentrations are inter-related, using a Fick's law diffusion equation involving a flow-rate-dependent mass transfer coefficient across the local diffusion boundary layer. Here, the flow distribution among all cells is assumed to be perfect. The Redox kinetics equations are modified to account for the presence of a flooded diffusion electrode deposit, using the approach described by Austin (42).

Lastly, procedures were suggested to establish the likely values of the electrode reaction transfer coefficient and the concentration dependence of the apparent exchange current density.

The Redox kinetic expressions are incorporated into an internal reactant material balance that is used in conjunction with a step-wise marching procedure down the flow path length of the Redox cell. Local values of the current density are calculated, consistent with the imposed (assumed) cell voltage and the local reactant concentrations and mass transfer conditions. The iterative procedures involved were discussed briefly in Section 3.3.3.1 and are covered in greater detail in the documentation package.

3.3.3.4 Redox Cell Mass Transfer Coefficients

The mass transfer coefficient estimation routines incorporated in the Stage 2 Model are based on the recent, extensive studies carried out by Landau and Tobias (43). Prior to selecting the Landau correlations, the literature on mass transfer effects and cell design for electrochemical systems was reviewed briefly. This design reference bibliography was assembled and is presented in Appendix 5-4. The Landau correlations were developed using electrochemical techniques and appear to be quite suitable for characterizing mass transfer from the bulk phase to the electrode surface in two dimensional channel geometries. The correlations are valid for laminar and turbulent flow within the Redox cell. Again, full details are given in the documentation package.

3.3.3.5 Membrane Considerations

The Redox cell designs currently being studied at NASA and elsewhere employ an ion-selective membrane to separate the electrolyte flow chambers. Typically, an anion-selective membrane is used with systems employing cations as reactive species. In principle, only the anions associated with the supporting electrolyte, say Cl^- , will pass selectively through the membrane, providing an ionically conductive path to complete the cell circuit. Cations, such as Fe^{+2} , Fe^{+3} , Ti^{+3} and Ti^{+4} would be excluded. In operation, there would be a net flux of Cl^- across the membrane in one direction during charging, and in the reverse direction during discharge. This ideal operation poses no special problems, from the point of view of the Stage 2 Model.

On the other hand, a brief review of the literature on ion-selective membranes revealed some disturbing phenomena (44-46). These are highlighted below:

- In general, ion-exchange membrane selectivity decreases as the concentration level increases. Thus, the ability to exclude cations will decrease as more concentrated Redox storage solutions are used. This Donnan effect will result in cross-transport of reactive cation species from one chamber to another, perhaps influencing the local reaction kinetics. At the very least, the effective concentration of reactive species in the desired chamber will decrease, lowering the solution energy density. Unfortunately, it is desirable to use high concentrations to maximize the energy density, thus reducing investment costs associated with solution tankage and flow lines.
- Concentrated solutions of reactive cations in supporting electrolyte usually form charged complexes, such as:



These complexes can affect local reaction kinetics, and may also move across the membrane slowly as equivalent anions. Again, complexing is usually responsible for the high apparent solubility that is needed for increased energy density.

- Substantial amounts of water can be transported across the membrane via electro-osmotic effects. This complex effect can result in water flux rates exceeding 50 moles/Faraday, in the positive or negative direction, depending on ionic species and concentration, membrane composition, current density and local hydrodynamic conditions. The water flux seems to be lower in concentrated electrolyte solutions, perhaps due to lower water clustering around the moving ions. This effect can be quite important. Movement of water will change local bulk concentrations down the cell path, resulting in changes in reversible potential, solution physical and transport properties, local solubility limitations, electrolyte volumetric flow rates, storage tank ullage requirements, and local thermal effects due to heats of dilution.

In summary, the treatment of ion exchange membrane phenomena appears to be quite complex, even when specific membranes and solution compositions are known in advance. However, a generalized treatment of these important effects was considered beyond the scope of the current Stage 2 Model effort. The present Stage 2 Model assumes that no specific ion or water transfer occurs across the membrane. These effects could be introduced into the local material balance sub-routines in the future, pending availability of data on real systems.

3.3.3.6 Shuntage Currents, Flow Distribution and Thermal Effects

After reviewing a number of approaches to the problem of shunt current loss predictions, the model developed by P. Prokopius of NASA-Lewis was selected (47). This model was the most understandable and

flexible one uncovered. As noted above, the shuntage power loss is assessed within each Δt slice performance evaluation. This loss is treated as an equivalent auxiliary power loss.

The shunt current model is used for the series-connected substack assembly, using the average cell current density, i , as load current. It is recognized that shunt current paths are present in the anolyte and catholyte manifolds between substacks within a stack. However, insufficient time was available to program a general form of the revised set of current balance equations. Also, shuntage current losses between stacks and between trailers are neglected. Here, it is assumed that piping connections are long enough to minimize shuntage.

These shuntage current calculations are carried out on an ex post facto basis. There is no feedback iterative provision for adjusting individual cell performance estimates, taking into account shuntage current effects. This level of sophistication is well beyond the scope of the Stage 2 Model.

Effort was expended to develop a general approach to the analysis of intra-stack flow distribution and stack pressure drop. A closed set of equations was devised for the relationship between local flow rates and point-by-point pressures at sections within the manifolds and across the cells. This was done for the flow scheme selected earlier, and shown in Figure 3-16. Here, an expanded, equivalent hydraulic flow network for the stack is presented. Once the geometric configuration of end plate manifolding and cell entry port designs are established, the flow distribution through the stack can be analyzed for fixed values of cell thickness, entry port diameter and length, etc. Account is taken of the difference between laminar and turbulent flow. The manifold analysis includes an assessment of local frictional pressure drop losses and the effects of momentum recovery on pressure at each flow branch point (into or out of a cell). This analysis is an expanded version of the perforated-pipe distribution problem described by Acrivos(48) and Greskovich(49).

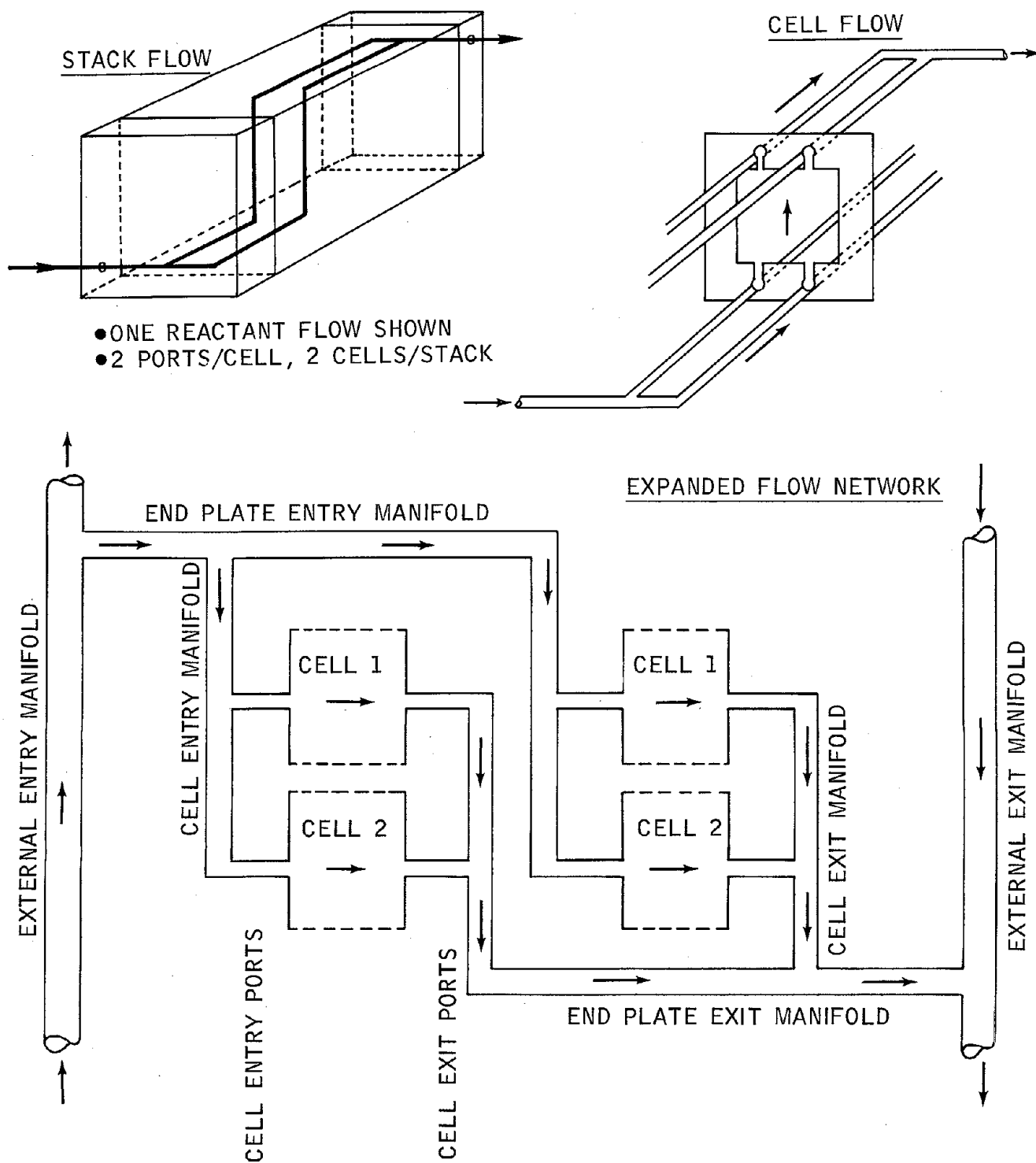
The cell pressure drop contributions were also analyzed, for local laminar or turbulent flow conditions, including the effect of:

- + Contraction from the entry port
- + Flow through the entry port
- + Expansion into the active cell area
- + Flow in the active cell area
- + Contraction into the exit port
- + Flow through the exit port
- + Expansion into the exit manifold
- + Overall change in elevation between manifolds.

Lundgren's analysis for contraction and frictional losses for laminar flow in rectangular ducts was used(50). Perry's Handbook was used for turbulent flow expansions and contractions and friction factors(51).

Figure 3-16

Flow Scheme Through Stack



Unfortunately, insufficient time was available to program the flow distribution and pressure drop analysis and to incorporate the subroutine into the Stage 2 Model. The programming procedures involved are not trivial. Derivation of the flow distribution model and suggested recursive computational techniques are given in Appendix 5-5. A subroutine based on this analysis could be used in the Stage 2 Model to assess the extent of flow mal-distribution in the Redox stacks and to assess the trade-off between pressure drop losses and improved mass transfer rates as reactant flow rates thru the cells are increased.

It should be noted that the Stage 2 Model does not carry out a system pressure balance and pressure drop calculation for the reactant flow circuits. Again, to do this in a general manner would be well beyond the scope of the Stage 2 Model effort.

Subsequent to this analysis, it was found that a similar study of flow distribution had been carried out at NASA (52) and that a comprehensive review of flow distribution manifolds was published by Bajura and Jones(53). The approach of these authors appears similar to the one described above. Also, a recent text by Jeppson reviews the general area of flow network analysis (54).

Lastly, thermal effects associated with Redox cell operation are estimated during each Δt time slice. The Stage 1 Model approach is used, resulting in an instantaneous value of cooler fan horsepower consumption. Coolers are sized and costed on the basis of the maximum duty noted during the complete weekly cycle. Note that thermal balance is assumed at all times. Thermal effect carryover into the storage tank system is neglected.

3.3.3.7 Other Design and Costing Features

The Stage 2 Model includes procedures for tankage, pump and filter design and costing, as well as reactant solution costing. As noted earlier, the user must specify an initial reactant inventory. This may be apportioned into multiple tanks, using Stage 1 Model logic. During operation of multiple tank systems, the Stage 2 Model assesses the state-of-charge of each tank contents. Tanks are dispatched sequentially. The Stage 2 Model logic also includes procedures for estimating the tank compositions, assuming a well-mixed tank model. Tank costing procedures are identical with those in the Stage 1 Model.

The Stage 1 Model routines are also used for the pump section. The size and cost of the pump system are based on the maximum flow rate encountered during the user-imposed duty cycle.

For the filtration section, the conservative external cartridge filter design used in the Stage 1 Model was retained. Other filter designs and placement were considered, as discussed in a later section.

3.3.3.8 Stage 2 Model Operation and Output

Final debugging of the Stage 2 Model took place during the writing of this report. Consequently, thorough evaluation of the model capability was not carried out. Initial results suggest that the model is responsive to changes in cell design and operating parameters. The completed Stage 2 Model contains about 110 user-specified input parameters, so that a complete exploration of all reasonable parameter interactions would take significant time and effort. This time pressure was recognized at the outset and a substantial number of user-adjusted software factors are included to permit fine-tuning of the model, as experience warrants. In particular, the number of iterations required to achieve imposed tolerance closure levels in many iterative loops simply is not known. Therefore, the user is given the opportunity to adjust the maximum permissible iterations for each loop. A set of output signals is incorporated into the Stage 2 Model print-out to alert the user that unexpected operating limits have been reached. This flexible approach should make the model quite adaptable to future learning experience. These features are discussed further in the documentation package.

To analyze a specific energy storage application, the user would be expected to define a complete charge/discharge power profile, along with the required (assumed) Stage 2 Model parameter values. A search technique would be initiated, using combinations of the major input variables: the number of Redox trailers and the reactant inventory. The Stage 2 Model output will provide the following information:

- + Ability to meet the imposed duty cycle: delivered discharge power and time versus charge power and charging time consumed, consistent with assigned operating limits (reactant concentration or cell voltage levels, etc.).
- + Total installed investment cost for successfully completed duty cycles.
- + Reactant inventory profile, so that extent of reactant under or over-utilization can be assessed.

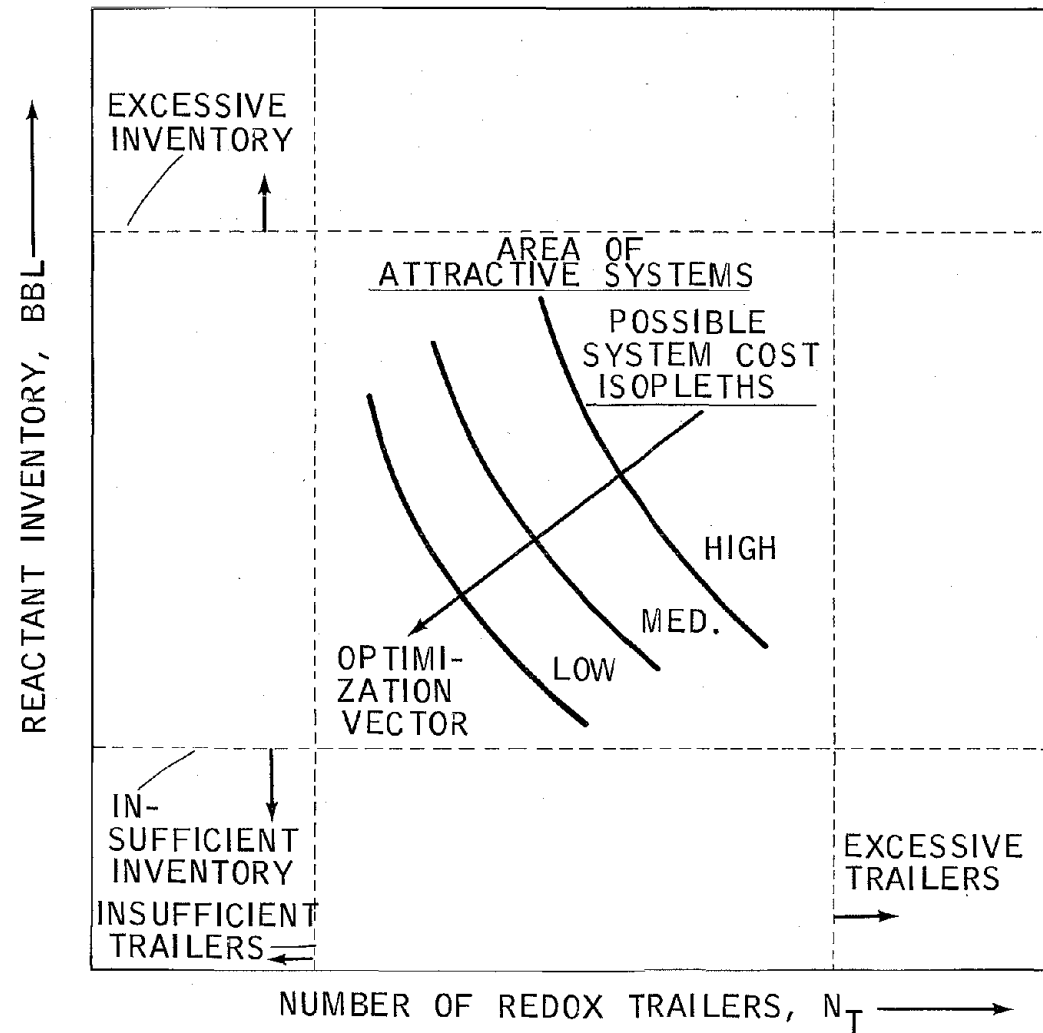
An output matrix would evolve that could be displayed graphically, as shown hypothetically in Figure 3-17. Classical procedures could then be used to search for optimal combinations of trailer number and reactant inventory, leading to minimum investment cost for energy storage systems that satisfy the required duty cycle.

3.3.4 Redox Energy Storage Systems Analysis

An extensive analysis was carried out, using the Stage 1 and 1.5 Models, to assess the feasibility of the Redox energy storage system. The models were used to project the total installed cost of Redox systems over the full range of potential daily and weekly energy storage cycle applications. A sensitivity analysis was also carried out to define the response of total system cost to changes in the model input parameter values and to identify major cost centers in the Redox battery concept.

Figure 3-17

Hypothetical Output Map for Stage 2 Model Results



3.3.4.1 Redox Model Parameter Values

The Stage 1 and 1.5 Models contain many parameters whose values must be assumed or chosen by the user. Suggested base-line values for these parameters were developed, together with possible ranges for the parameter values. In addition, an optimistic set of values was prepared, to explore the ultimate potential of fully-developed Redox battery systems. A complete description of the parameters, including definitions and suggested values, is given in Tables 3-21 and 3-22.

The base-line values noted in these tables were developed as follows:

- + The electrochemical and Redox couple property parameters were based on a conservative extrapolation of currently achieved Redox battery characteristics(38). A relatively low energy couple was assumed, together with hydrochloric acid as supporting electrolyte.
- + The membrane parameters were also based on demonstrated performance, at least for short time periods (55,56).
- + The Redox converter cell design was chosen on the conservative side. The cell frames were assumed to be polypropylene and graphite was assumed for the conductive structures.
- + The stack fabrication factor and Redox trailer internals, assembly and installation cost factors were based on previous experience with large-scale electrochemical facility designs.

3.3.4.2 Preliminary Analysis of Stage 1 Model Predictions

As an adjunct to the system studies, the Stage 1 Model logic was examined to define the likely bounds of performance that will meet the daily cycle application requirements. Using the relationships developed earlier and the baseline parameter values, the ideal storage efficiency (neglecting parasitic power consumption) was calculated as a function of imposed discharge time, t_D , and charge time, t_C . This relationship is given in Figure 3-18, which also shows the bounded area enclosed by the daily cycle application limits of t_C (5-9 hrs.) and t_D (1-14 hrs.). The loci of all sets of t_C and t_D values resulting in constant efficiency operation ($\eta = 0.5$ to 0.8)^c are also shown. For example, if $t_C = 5$ hrs. a target efficiency of 0.75 can be obtained when $t_D = 5.2$ hrs., and so on. Corresponding values of the ratio P_D/P_C are plotted versus efficiency in Figure 3-19. Again, a power ratio of $P_D/P_C = 0.727$ is required for an efficiency of 75 percent. It should be noted that the baseline parameter values yield a maximum efficiency of 82.5 percent, much higher than is probably required, based on the economic analysis presented in Section 3.2.

3.3.4.3 Analysis of Daily Cycle Energy Storage Systems

The Stage 1 Model was used to analyze the daily cycle applications for peaking and intermediate duty energy storage systems, as defined in Section 3.2. A mini-matrix of computer runs was evaluated consisting of all combinations of:

Table 3-21

Parameters Specified in NASA Stage 1 Model Outline

<u>Symbol</u>	<u>Definition</u>	<u>Computer Program Notation</u>	<u>Units</u>	<u>Baseline Value</u>	<u>Suggested Range of Parameter Values</u>
ϵ_R	AC to DC rectifying efficiency	ER	-	0.95	0.9-0.98(0.98)**
ϵ_I	DC to AC inversion efficiency	EI	-	0.95	0.9-0.98(0.98)
ϵ_T	Cell thermal efficiency	ET	-	1.00	0.8-1.2(1)
ϵ_{FC}	Faradaic cell efficiency during charge	EFC	-	1.00	0.8-1.0(1)
ϵ_{FD}	As above, discharge	EFD	-	1.00	0.8-1.0(1)
V_c	Converter charging voltage	CAPVC	volts	500	200-1500(1500)
i_c	Time-averaged charging current density	IC	amps/cm ²	0.100	0.01-0.50(0.5)
a_G, a_D	Coefficients in expression for non-ohmic polarization, charge or discharge	AC, AD	volts	0.0	* (0)
b_G, b_D	As above	BC, BD	volt cm ² /amp	0.50	0.0-0.2(0)
V_R	Time-averaged reversible cell voltage	VR	volts	0.8	0.4-1.5(1.5)
δ	Membrane thickness	DELTA	cm	0.010	0.002-0.015(0.002)
ρ	Membrane specific resistivity	RHO	ohm cm	25	10-100 (0)

* Generally, this parameter will = 0, but linear approximations of Tafel equation at high current could yield effective negative values.

** Optimistic parameter values are indicated paranthetically.

1
8
1

Table 3-21 (Continued)

<u>Symbol</u>	<u>Definition</u>	<u>Computer Program Notation</u>	<u>Units</u>	<u>Baseline Value</u>	<u>Suggested Range of Parameter Values</u>
n_p	Number of parallel cells	NP	-	**	***
u	Reactant utilization factor	U	-	1.0	0.5-1.0(1)
f_{1c}, f_{2c} f_{1D}, f_{2D}	Solution flow rates per cell, charge and discharge for reactants 1 and 2	F1C, F2C F1D, F2D	- -	1.0 1.0	1.0-2.0(1,1) 1.0-2.0(1,1)
MW_1, MW_2	Reactant molecular wt. (Complete compound basis, i.e., $FeCl_3$ not Fe)	MW1, MW2	gms/gm mole	150	75-250(150)
Z_1, Z_2	Electrons transferred per mole	Z1, Z2	eq/gm mole	1	1-3(3,1)
C_1, C_2	Initial concentration of reactants 1 and 2	C1, C2	gm moles/liter	1	1-5(5,5)
C_{1S}, C_{2S}	Supporting electrolyte concentration	C1S, C2S	gm moles/liter	5	1-10(5)

*** The Stage 1 Model calculates the cell area using n_p . In order to keep projected cell size approximately constant as given charging power (P_c) is changed, we recommend using $n_p \sim 12P_c$, where P_c is in MW. The Stage 1.5 Model was modified to permit the direct entry of desired cell size.

Table 3-22

Additional Parameters Included in Final Stage 1 Model

<u>Symbol</u>	<u>Definition</u>	<u>Computer Program Notation</u>	<u>Units</u>	<u>Baseline Value</u>	<u>Suggested Range of Parameter Values</u>
$\bar{\rho}_{\text{SOL}(1)}, \bar{\rho}_{\text{SOL}(2)}$	Average solution density, reactant + electrolyte	RHO1, RHO2	gms/cm ³	1.05	1-2(1.05)*
$\bar{C}_{\text{P1}}, \bar{C}_{\text{P2}}$	Average solution heat capacity	CP1, CP2	cal/gm°C	0.8	0.7-1.0(0.8, 0.8)
MW _{SE}	Molecular weight of supporting electrolyte	MWSE	gms/gm mole	36.4	30-150(36.4)
$C_{\text{R}(1)}, C_{\text{R}(2)}$	Delivered cost of reactant solutions	CR1, CR2	\$/kg	0.5	0.5-10.0(0.5, 0.5)
C_{SE}	Delivered cost of supporting electrolyte	CSE	\$/kg	0.12	0.1-1.0(0.12)
e	Electrode deposit thickness (on either side of membrane)	EE	cm	0.01	0.005-0.05(0.005)
τ	Flow channel thickness	TAU	cm	0.05	0.02-0.2(0.02)
γ_{c}	Current collector thickness	GAMMAC	cm	0.60	0.1-0.8(0.1)
γ_{E}	End plate conductor thickness	GAMMAE	cm	1.50	1-2(0.1)
ρ_{E}	Apparent bulk density of electrode deposit	RHOE	gm/cm ³	0.5	0.4-2.0(0.4)
ρ_{cp}	Density of cell plastic	RHOCP	gm/cm ³	0.9	0.8-2.2(0.8)
ρ_{cc}	Density of current collector material	RHOCC	gm/cm ³	1.8	1-3(1.8)

* Optimistic parameter values are indicated paranthetically.

Table 3-22 (Continued)

<u>Symbol</u>	<u>Definition</u>	<u>Computer Program Notation</u>	<u>Units</u>	<u>Baseline Value</u>	<u>Suggested Range of Parameter Values</u>
δ_{SW}	Stack installation clearance, width	DELT SW	cm	30	20-40(20)
δ_{SH}	Same, height	DELT SH	cm	20	10-30(10)
δ_{SL}	Same, length	DELT SL	cm	30	20-40(20)
T'_H	Shippable trailer external height	THUS	ft	10	Fixed
T'_W	Same, width	TWUS	ft	10	Fixed
T'_L	Same, length	TLUS	ft	40	Fixed
Δ_T	Trailer inboard clearance	DELT T	cm	30	20-40(20)
T_{cell}	Converter operating temperature	TCELL	°C	50	25-80(50)
T_{air}	Ambient air temperature	TAIR	°C	25	5-40(25)
$f_{I(1)}, f_{I(2)}$	Solution inventory factor*	FI1, FI2	-	1.05	1.0-1.1(1,1)
$f_{TU(1)}, f_{TU(2)}$	Tank ullage factor**	FTU1, FTU2	-	1.1	1.0-1.2(1,1)
C_{cp}	Cost of cell plastic	CCP	\$/kg	0.57	0.5-15(0.5)
C_{cc}	Cost of cell current collector material	CCC	\$/kg	3.30	1-10(1)
C_E	Cost of cell electrode deposit	CE	\$/kg	2.20	1-10(1)
C_M	Cost of cell membrane	CM	\$/m ²	9.0	1-20(1)

* Ratio, $\frac{\text{Total solution inventory volume}}{\text{solution inventory for calculated charge}}$

(Accounts for reactant hold-up volume in process equipment and cells.)

** Ratio, $\frac{\text{Nominal tank volume}}{\text{Nominal liquid content}}$

Table 3-22 (Continued)

<u>Symbol</u>	<u>Definition</u>	<u>Computer Program Notation</u>	<u>Units</u>	<u>Baseline Value</u>	<u>Suggested Range of Parameter Values</u>
fm	Stack fabrication cost factor***	FM	-	2.5	2-3(2)
C _{TP}	Cost of trailer internal piping	CTP	\$/kw	5	5-15(2.5)
C _{TBB}	Cost of trailer internal busbar + electrical con- nectors	CTBB	\$/kw	10	5-20(5)
C _{TS}	Cost of trailer structurals	CTS	\$/kw	5	5-15(2.5)
C _{TI}	Cost of trailer instrumen- tation	CTI	\$/kw	5	5-15(2.5)
C _I	Trailer installation cost	CI	\$/kw	20	15-30(15)
C _{PCI}	Power conditioner instal- lation cost	CPCI	\$/kw	20	15-30(15)

*** Ratio, Fabricated stack cost
Stack material cost

Figure 3-18

Stage 1 Model Efficiency Predictions As
a Function of Charge and Discharge Time

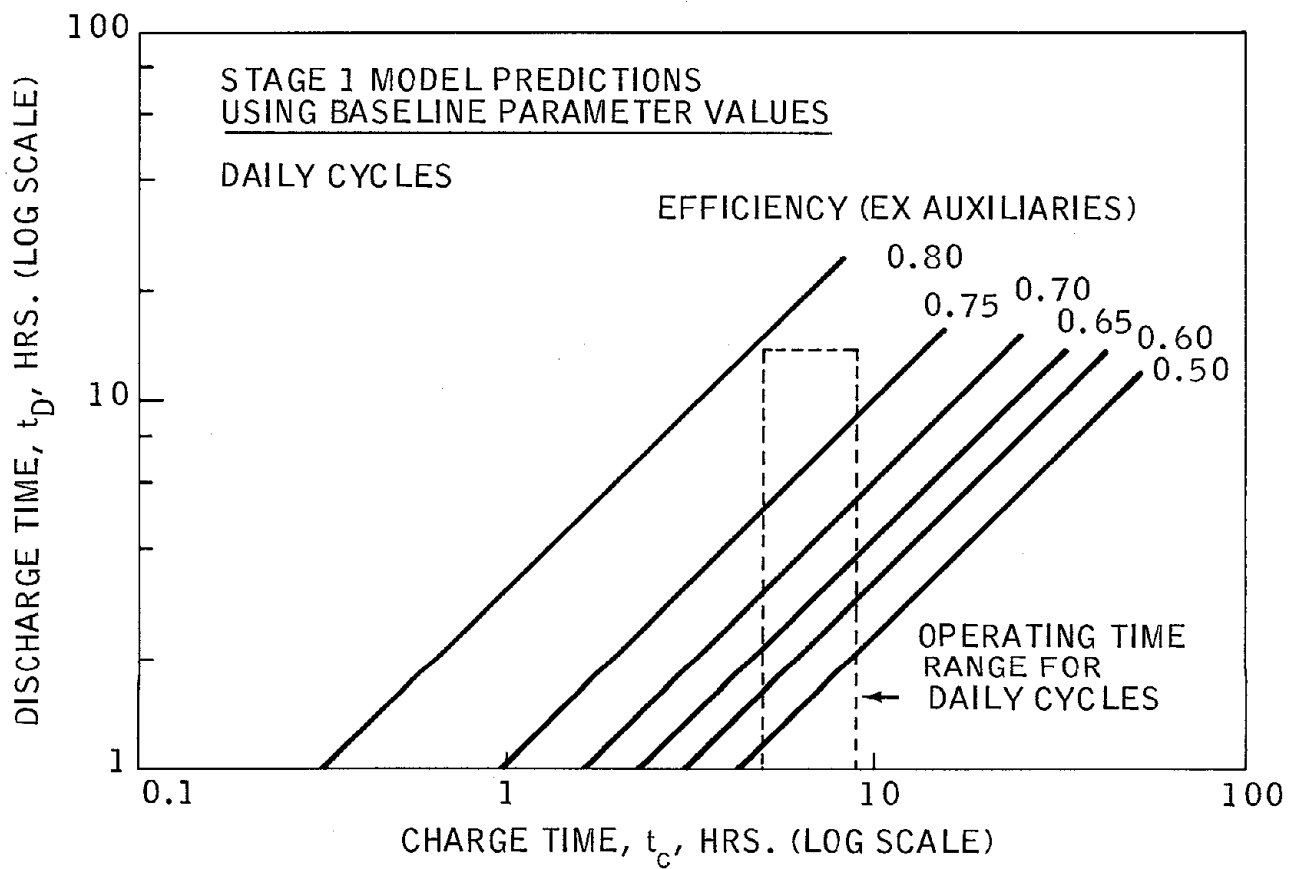
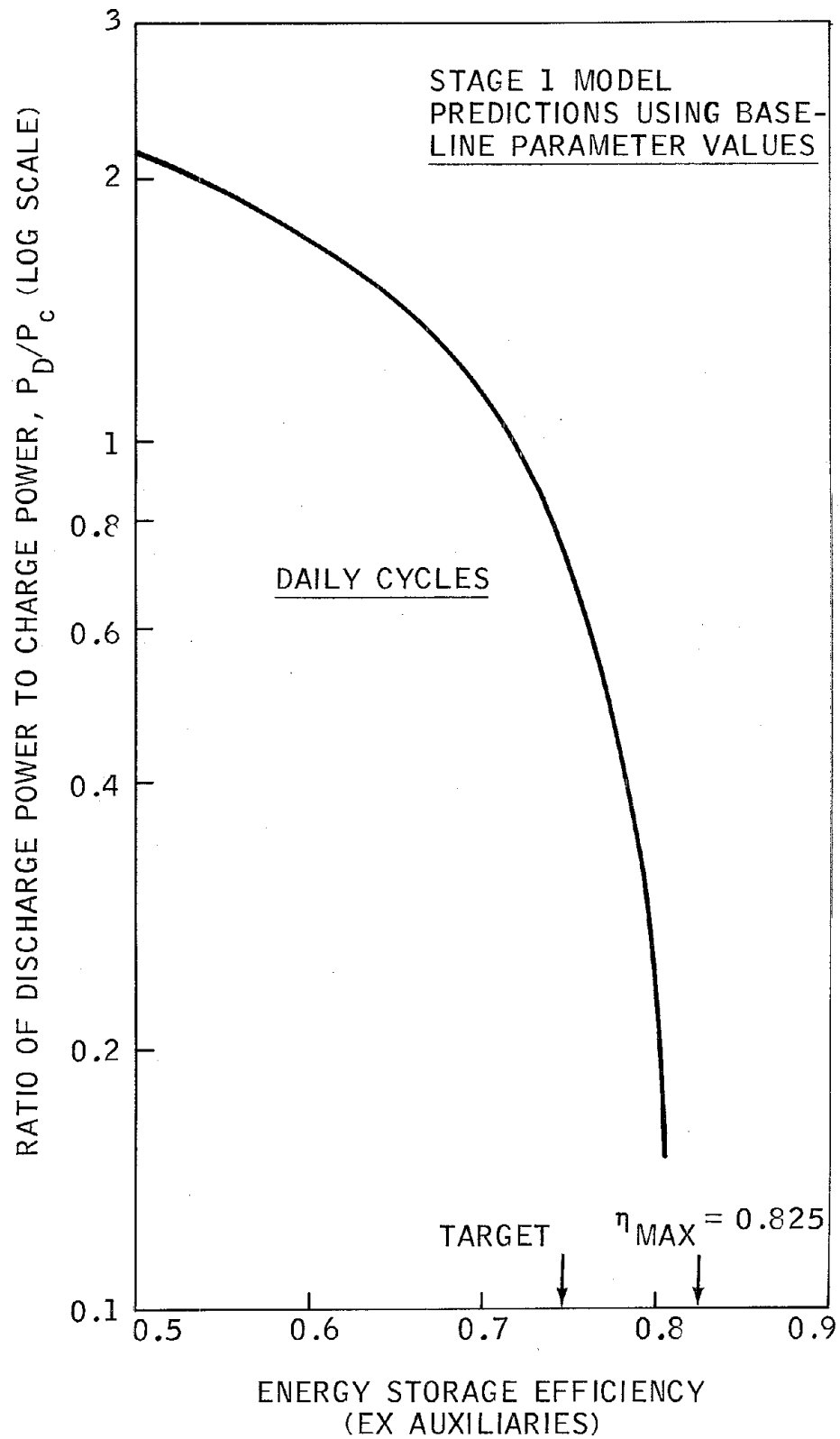


Figure 3-19

Stage 1 Model Power Ratio Predictions As
a Function of Energy Storage Efficiency



Discharge Power, $P_D = 10, 100, 1000 \text{ MW}$

Discharge Time, $t_D = 1, 4, 7, 10, 13 \text{ hrs.}$

Charge Time, $t_c = 5, 7, 9 \text{ hrs.}$

The typical effect of charge/discharge time on installed power investment costs is shown in Figure 3-20. Here, the investment costs are expressed as \$/KW, based on the net discharge power level. For a fixed charge time, the system cost exhibits a shallow minimum as required discharge time is increased. In general, the minimum occurs near the point where charge and discharge times are roughly equal. The reason for this appears to be the resulting balance in system flow rates in charge and discharge operating mode. This minimizes the associated filter section costs, a factor which will be discussed further below.

The major finding from these results is the general level of installed costs. Using the base-line parameter values, the minimum investment costs exceed 1000 \$/KW (based on discharge conditions). As expected, considerably lower investment costs were projected for Redox systems using the optimistic parameter values. Figure 3-20 also contains the range of break-even cost targets for advanced batteries in utility energy storage systems. These break-even costs were developed in Section 3.2. As indicated, the investment costs for Redox systems designed with conservative base-line parameter values are substantially higher than the target values. On the other hand, use of the optimistic parameters yields quite attractive investment costs. There appears to be considerable latitude in selecting Redox system parameter values yielding cost-effective energy storage systems. Clearly, the Stage 1 Model can be used to develop composite targets for Redox couple characteristics and system operation.

An alternative display of these results was used, plotting the energy investment costs, \$/KWH, versus the daily discharge time, as shown in Figure 3-21. The energy investment cost was calculated by dividing the power investment cost, \$/KW, by the system daily discharge time. Figure 3-21 includes estimates for the costs of lead-acid and projected advanced battery systems, discussed earlier in Section 3.1. The energy investment costs for these battery systems were calculated from:

$$\text{Lead Acid: } \$/\text{KWH} = \frac{100 + (65 \text{ to } 77) t_D}{t_D}$$

$$\text{Advanced Batteries: } \$/\text{KWH} = \frac{100 + 30 t_D}{t_D}$$

The energy investment cost range for base-line parameter Redox systems exceeds that of lead-acid batteries. However, costs for optimistic parameter Redox systems are lower than those projected for the advanced batteries, particularly for long discharge times. In general, Redox system operation in long discharge time cycles appears more favorable than in shorter, peaking cycles. This means that the Redox system has relatively large power-related cost components and relatively low energy-related costs. The latter was expected.

Figure 3-20

Effect of Charge/Discharge Time on Daily
Cycle Redox System Investment Costs

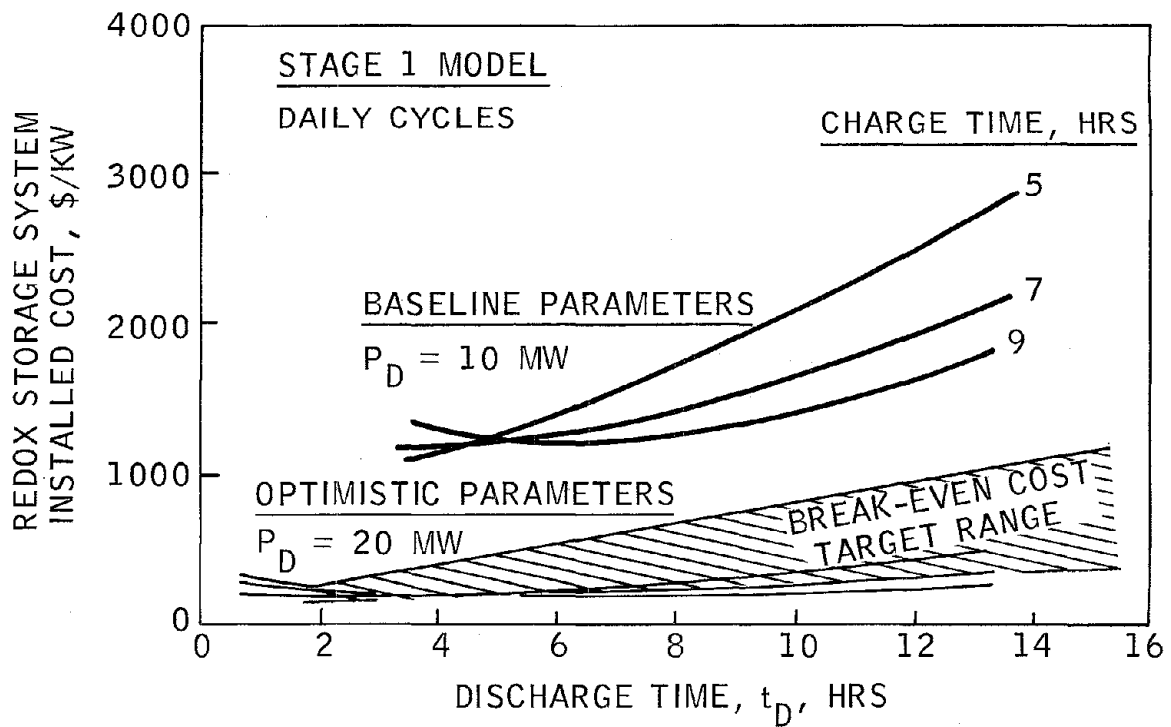
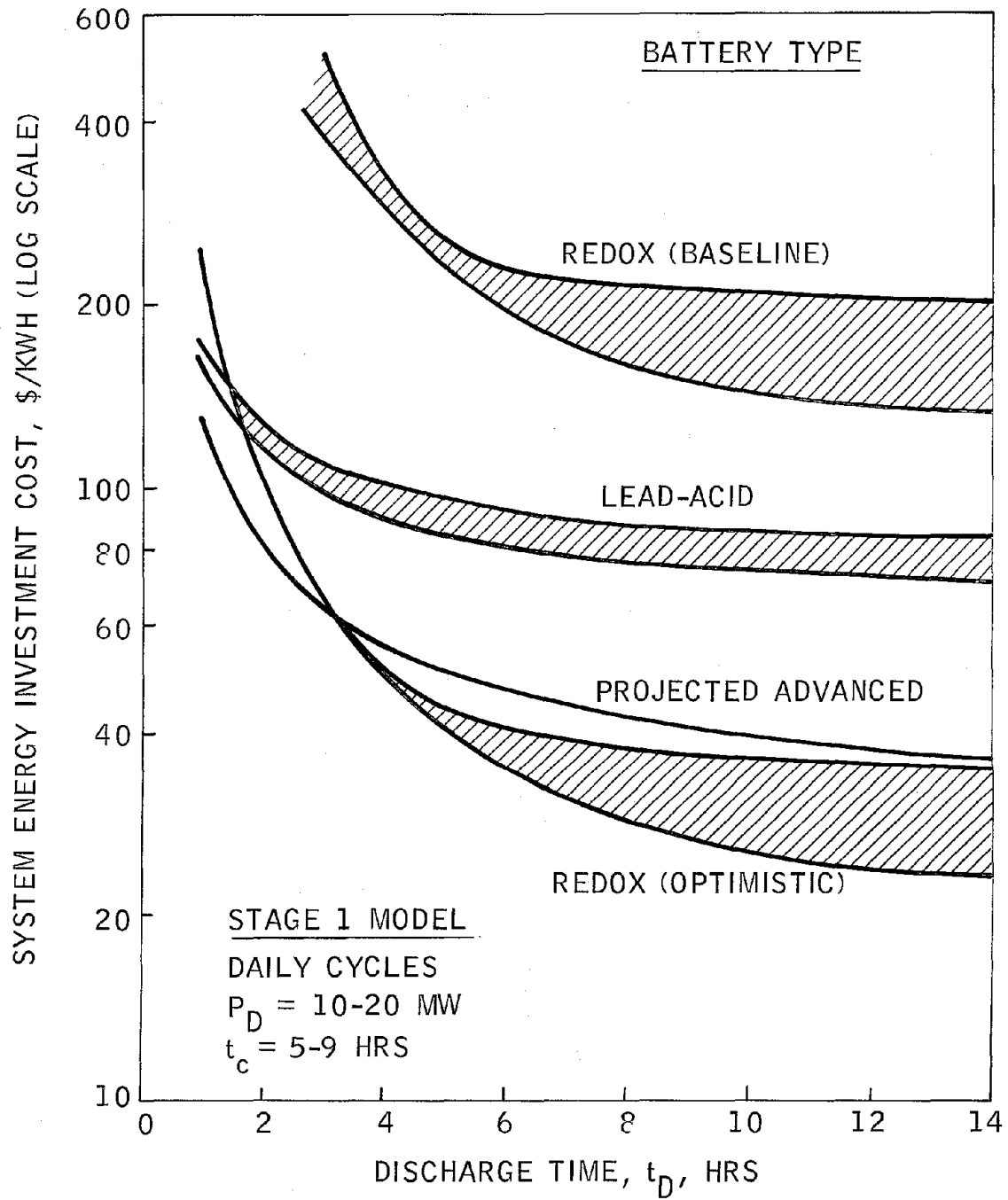


Figure 3-21

Energy Investment Costs Look Good
For Redox Case Using Optimistic Parameters



The daily cycle system cost estimates were analyzed in more detail. A typical distribution of sub-system installed costs is shown in Table 3-23, using the base-line and optimistic parameter values.

Table 3-23

Sub-System Cost Distribution for Daily Cycle Redox Battery Systems

<u>Installed Sub-System</u>	<u>Baseline Parameters</u>		<u>Optimistic Parameters</u>	
	<u>\$/kw</u>	<u>%</u>	<u>\$/kw</u>	<u>%</u>
Tankage	100	10	19	9
Pumps	27	3	6	3
Filters	409	38	25	12
Coolers	121	12	29	14
Redox Trailers	208	20	29	14
Power Conditioner	135	13	86	43
Reactants	45	4	11	5
	<hr/> 1045 \$/kw		<hr/> 205 \$/kw	

$\delta_D = 20$ MW (Daily cycle)

$t_c = 5$ Hrs. $t_D = 4$ Hrs.

Additional results from this analysis are displayed in Figure 3-22. The following points can be made:

- The filter costs are clearly excessive and must be reduced. Possibilities here include:
 - + Alternative filtration technologies, such as sand bed filters, that provide lower cost in scaled-up configurations. The problem here would be to find chemically stable filtration media and to assess the particle size removal characteristics of deep bed filters.

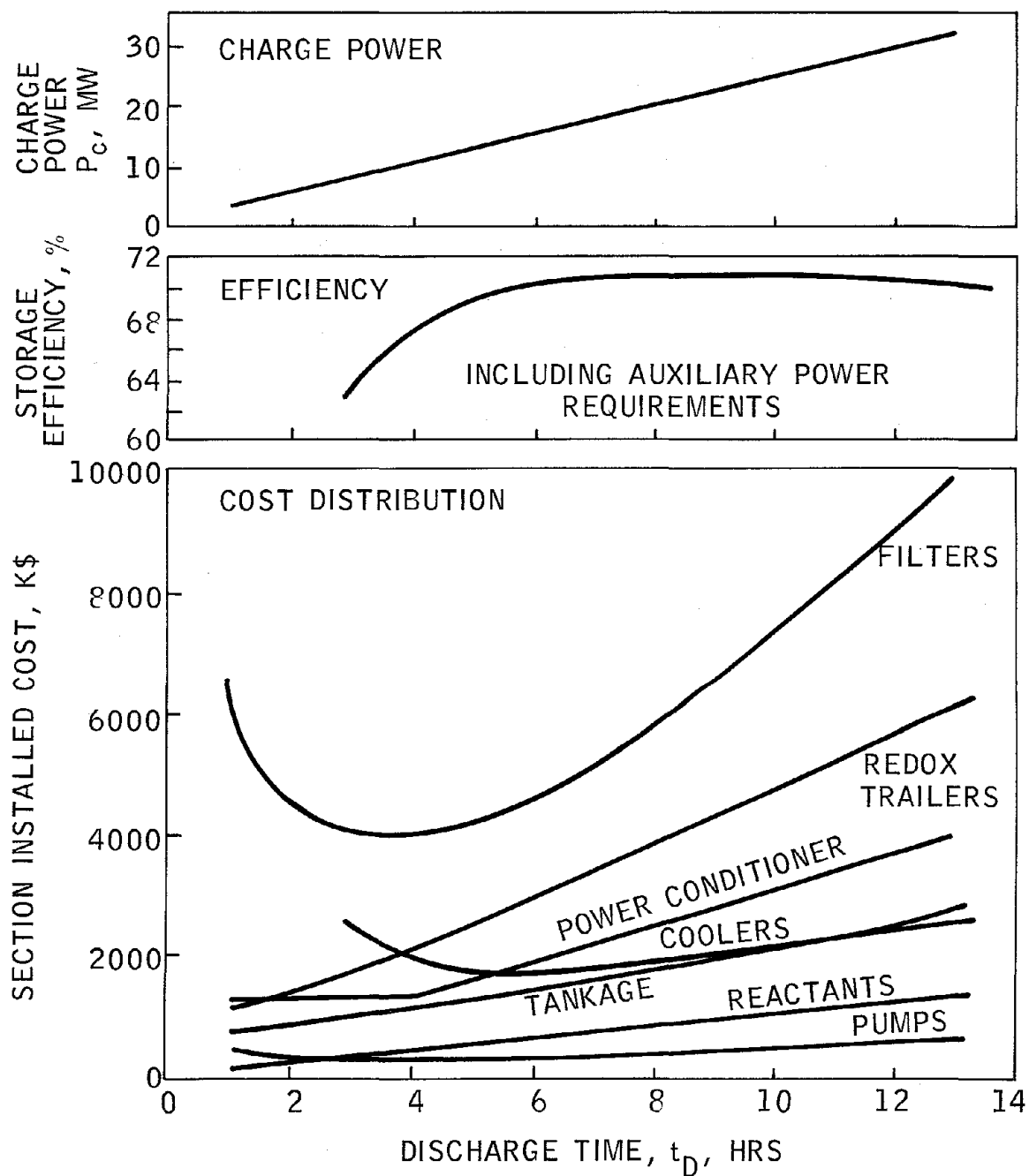
Figure 3-22

Composite Display of Typical Stage 1 Model Results for Duty Cycles

DISCHARGE POWER, $P_D = 10$ MW

CHARGE TIME, $t_c = 5$ HRS

BASELINE PARAMETERS



- + Use of by-pass filtration schemes, with only part of the flowing reactant stream passing thru the current cartridge filter equipment at any one time. This approach would affect the reliability and/or life of the Redox converter equipment.
 - + A variation of the above would be to by-pass the filter section entirely during the charge and discharge operation. Instead, the stored reactants would be filter polished by recycling through the filter section during the time periods between charge and discharge operation. The problem here is to ensure that the filter throughput capacity and pump capacity are large enough to accomplish the required polishing in the available inter-operating time period. Of course, a parasitic power requirement is involved during this pumping/filtration period. This will reduce somewhat the overall system energy storage efficiency, but the (hopefully) lower costs associated with a smaller filter section could make the approach attractive.
 - + The current maximum filter flow rate of 275 gpm is an estimate based on a probable allowable pressure drop of 15 psi across the filters. Nominal filter particle retention size is assumed to be in the 50-100 μ range. Perhaps the minimum critical dimensions in the Redox converter (probably the entry port zone) could be increased in size to permit the use of larger pore filtration cartridges having lower pressure drop. This could permit increased capacity per filter, perhaps increasing the current 275 gpm limit to 1000 gpm or so. In turn, this would reduce the number of filter assemblies, resulting in lower overall costs.
 - + Another opportunity for major cost reduction would be to replace the present external filter assembly with porous plate filter discs located within the Redox converter trailer, perhaps on the inlet manifold lines to each stack module. Again, additional study is needed to ensure that compatible filtration action and flow rate capacity can be obtained, consistent with the stack reactant flow rate requirements. The major problem here would involve a more labor-intensive maintenance program to replace plugged filters, together with the periodic removal of Redox trailers from active service during the maintenance periods.
- The Redox trailers are the next most expensive item (for the base-line parameter case). Here, considerable opportunity exists for future optimization of component (plastic) thickness and for adjusting the estimated costs of associated installation requirements.
 - Power conditioning costs also seem somewhat high, but these costs are based on estimates made by Westinghouse for EPRI.(39) Perhaps future optimization and selection of balanced charge/discharge operation could reduce these costs. Occasional projections to the 50 \$/KW level have appeared in the literature.

- The tankage section costs were examined in some detail. On average, the following distribution of costs in the tankage section was found:

<u>Item</u>	<u>% of Total Installed Cost</u>
Tankage (delivered and erected)	20
Tank and spillwall PVC lining	26
Mixers and foundation	9
Other (spillwalls, manifolds, all piping and pipe lining, tank paint and insulation)	45

The relative contribution of "other" items to the total cost appears to increase as tank size increases. Again, the piping and manifold costs in the Stage 1 Model are gross values based on initial estimates of line sizes associated with some high volume tankage systems.

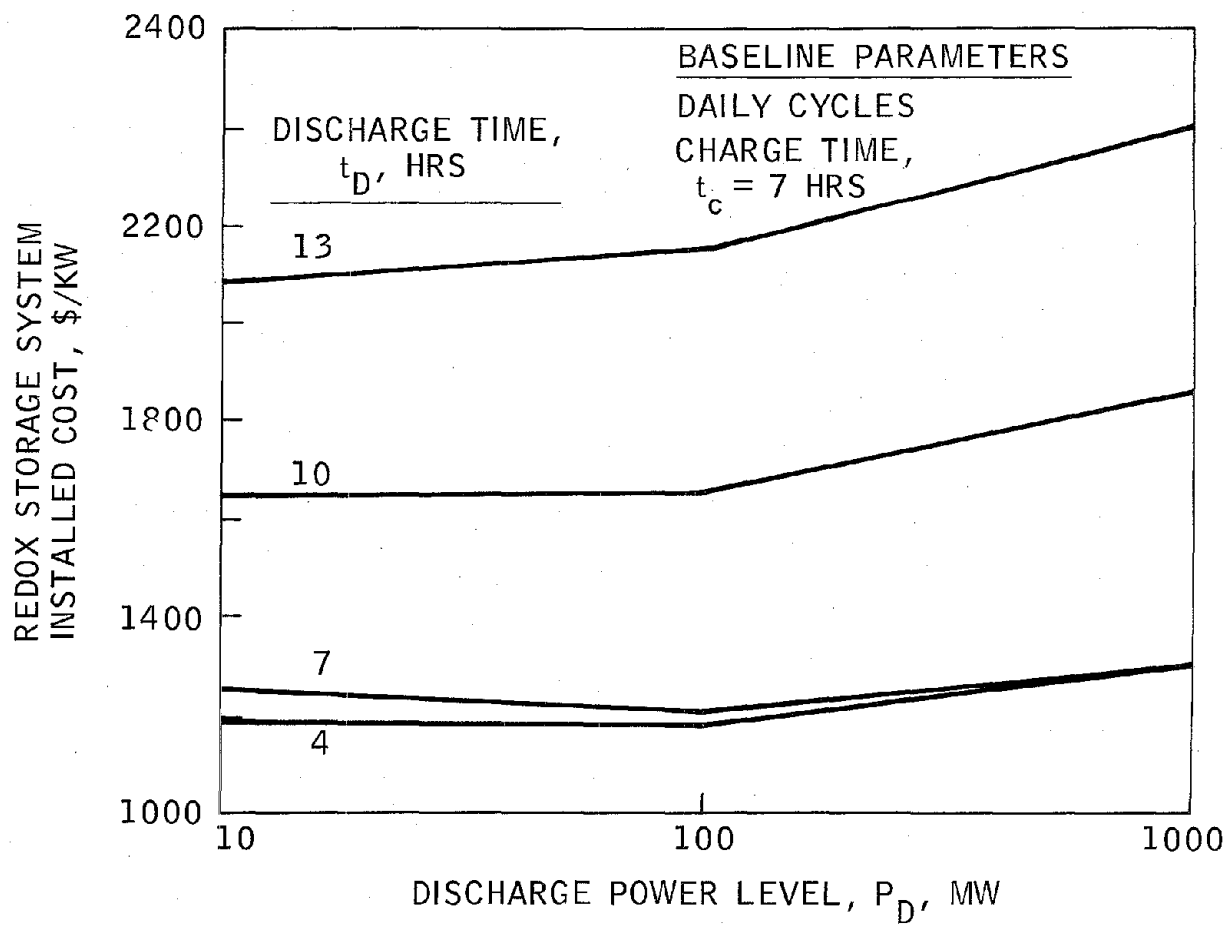
It should also be noted that the Stage 1 Model approach to providing spare tankage can be optimized, within limits. For example, if each reactant requires a 200,000 bbl tank for storage, a third 200,000 bbl tank is used as the required spare. Preliminary calculations show that some savings can be made by using two 100,000 bbl tanks for each reactant and adjusting the size (and cost) of the single spare tank to 100,000 bbl capacity. Additional study is required to define the optimal size, but the Stage 1 Model costing procedures are not sensitive enough. It will be recalled that the "tankage section" costs include piping and manifolding components, and the effect of these items on total cost will influence the determination of optimum tank size and number.

Figure 3-22 shows the corresponding efficiency and charge power for the cases depicted. In general, the efficiency levels (including auxiliary power requirements) are attractively high. In addition, Figure 3-22 shows how varying the discharge time (at constant charge time = 5 hrs) can affect the balance between discharge power level (fixed at 10 MW) and the required charge power level.

The computer results were also analyzed to determine the effect of system power level (size) on cost. As shown in Figure 3-23, there appears to be no real "economy-of-scale" effect. The modular nature of the Redox converters, filters, air fin coolers and power conditioning results in substantially constant \$/Kw costs.

Figure 3-23

Effect of Scale on Redox System Investment Costs



Lastly, it was noted that daily cycles with short discharge time ($t_D = 1$ hr) resulted in required cooler effluent temperatures below ambient temperature (25°C). The effect of increasing the solution flow rates from the base-line value ($f_D = 1$) was evaluated. The effect of doing this on system costs is shown in Figure 3-24. Only the filter, pump and cooler costs were affected. As shown, there is a trade-off between pump and cooler cost as flow rate is increased. However, this trade-off effect is swamped by the abnormally high filter costs noted previously. Incidentally, flow rates above $f_D = 2$ were required to obtain thermodynamically possible exit temperatures.

3.3.4.4 Sensitivity Analysis for Daily Cycle Energy Storage Systems

A sensitivity analysis was carried out using the Stage 1 Model to assess the impact of parameter variations on the predicted investment cost of the Redox battery system. Each parameter in the model was varied independently over the range of likely parameter values. This analysis was carried out for a fixed daily cycle operational system having discharge power, $P_D = 20\text{MW}$, charge time, $t_c = 5$ hrs and discharge time, $t_D = 4$ hrs. Previous analysis showed that this power level was typical for storage systems at the substation level and that the operating times yielded minimum installed investment costs. The baseline parameter values gave a system investment cost of 1045 \$/Kw (based on discharge power). This is the un-adjusted cost, including full filtration subsystem, etc.

The specific parameter values explored and the resulting impact on investment cost are displayed in Table 3-24. The cost sensitivities were analyzed and the parameters were grouped according to their effect as:

- Major impact parameters ($\pm 20\%$ change in cost)

- + v_R
- + i_c
- + C_1, C_2
- + Z_1, Z_2
- + E_{fc}, E_{fD}
- + $f_{1c}, f_{1D}, f_{2c}, f_{2D}$
- + ϕ
- + C_{cc}

- Secondary impact parameters ($\pm 10\%$ change in cost)

- + b_c, b_D
- + E_T
- + u
- + T_{air}
- + γ_c
- + $C_{R(1)}, C_{R(2)}$

- Minor impact parameters ($< 10\%$ change in cost)

- + All remaining parameters

Figure 3-24

Effect of Flow Rate on Section Costs

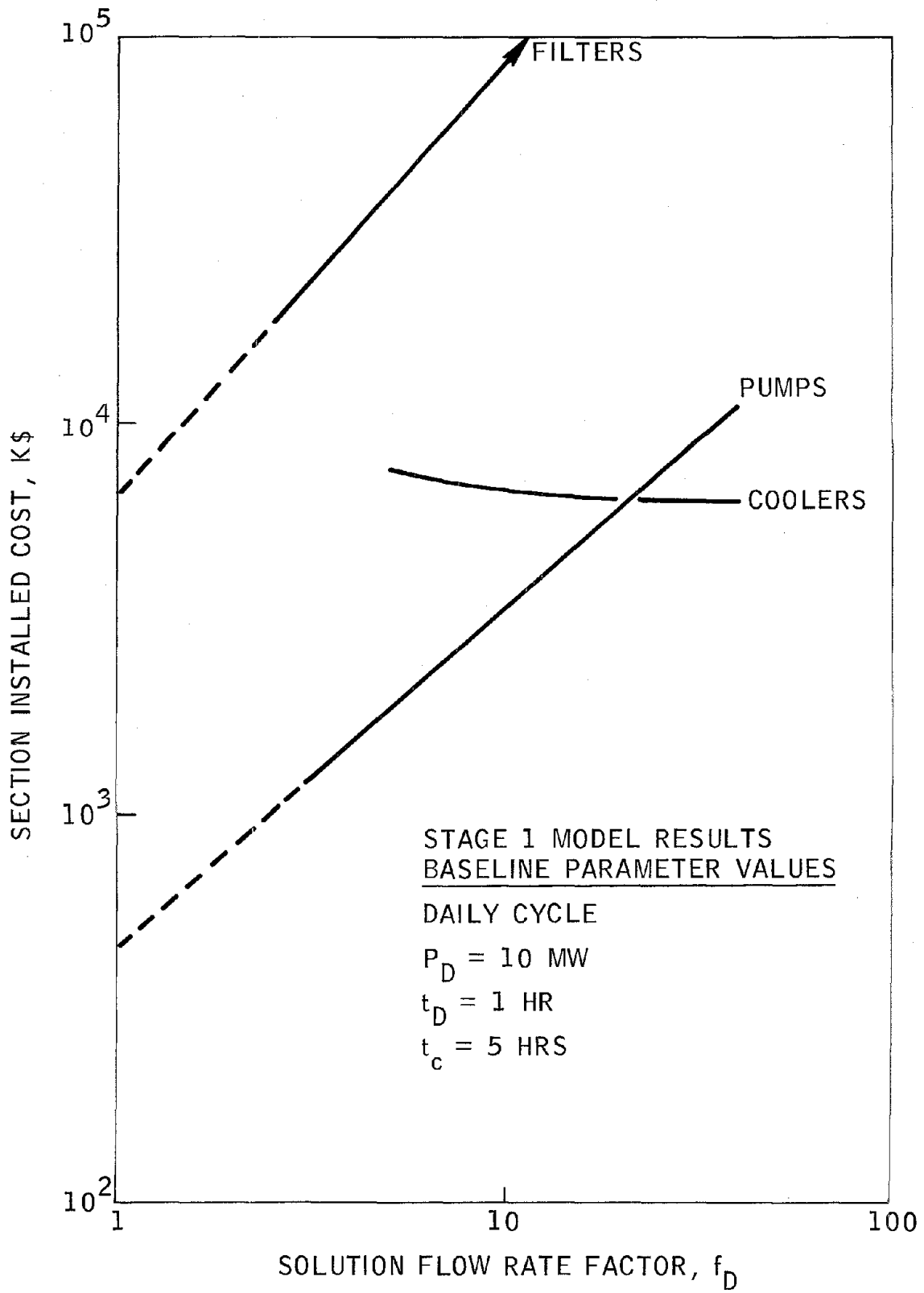


Table 3-24

Sensitivity Analysis of Baseline Redox System

Baseline Parameter Case: $P_D = 20 \text{ MW}$, $t_a = 5 \text{ hrs}$, $t_D = 4 \text{ hrs}$

Total Investment Cost (based on discharge) = 1045 \$/Kw

Parameter Grouping	Parameter			Parameter Values			Effect on Baseline Investment Cost with Indicated Parameter Value, \$/Kw		Optimistic Parameter Value	Notes
	Name	Symbol	Units	Min	Baseline	Max	Min	Max		
● Redox Couple Parameters										
+ Electrochemical	Reversible cell voltage	V_r	volts	0.6	0.8	1.0	+340	-185	1.5	(1)
	Non-ohmic polarization	a_c, a_p	volts	-	0,0	-	--	--	0,0	(2)
	Non-ohmic polarization	b_c, b_p	volt cm ² /amp	0,0	0.5,0.5	1,1	-123	+166	0,0	--
	Electrons transferred	Z_1, Z_2	eq/gm mole	-	1,1	2,2	--	-277	3,1	(3)
	Thermal efficiency	E_T	--	0.8	1	-	+195	--	1	--
	Faradaic efficiency	E_{fc}, E_{fd}	--	0.8,0.8	1,1	-	+428	--	1,1	--
+ Physical										
	Reactant molecular wt.	MW_1, MW_2	gms/gm mole	75,75	150,150	250,250	-18	+23	150,150	--
	Reactant concentration	C_1, C_2	gm moles/liter	-	1,1	2,2	--	-259	5,5	(4)
	Electrolyte concentration	C_{1s}, C_{2s}	gm moles/liter	1,1	5,5	10,10	-9	+10	5,5	--
	Electrolyte molecular wt.	MW_{se}	gms/gm mole	30	36.4	150	-2	+31	36.4	--
	Solution heat capacity	C_{p1}, C_{p2}	cal/gm°C	0.7,0.7	0.8,0.8	1,1	0	-1	0.8,0.8	--
	Solution density	$\rho_{sol(1)}, \rho_{sol(2)}$	gms/cm ³	1,1	1.05,1.05	2,2	0	-1	1.05,1.05	--
+ Cost										
	Reactant cost	$C_R(1), C_R(2)$	\$/kg	-	0.5,0.5	2	--	+105	0.5,0.5	(5)
	Electrolyte cost	C_{se}	\$/kg	-	0.12	1	--	+74	0.12	--
● Redox System Operational Parameters										
+ Redox Converter	Charging voltage	V_c	volts	200	500	1500	+54	-37	1500	--
	Charge current density	i_c	amps/cm ²	-	0.1	-	----- See Notes -----		0.5	(6)
	No. cells in parallel	n_p	--	----- See Notes -----			-1	0	--	(7)
	Reactant utilization	u	--	0.5	1	-	+117	--	1	--
	Solution flow rates	(f_{1c}, f_{2c}) (f_{1D}, f_{2D})	--	-	(1,1) (1,1)	(5,5) (5,5)	--	+2179	1,1 1,1	(8)
	Cell temperature	T_{cell}	°C	40	50	80	+47	-41	50	(9)
	Rectifying & inversion efficiency	E_R, E_I	--	0.90,0.90	0.95,0.95	0.98,0.98	+63	-35	0.98,0.98	--
	Ambient temperature	T_{air}	°C	5	25	40	-32	-130	25	--
	Solution inventory	F_{I1}, F_{I2}	--	1	1.05	1.1	-6	+5	1,1	--
	Tank ullage	f_{TU1}, f_{TU2}	--	1	1.1	1.2	-8	+7	1,1	--

Table 3-24 (Continued)

Sensitivity Analysis of Baseline Redox System

Baseline Parameter Case: $P = 20 \text{ MW}$, $t_c = 5 \text{ hrs}$, $t_D = 4 \text{ hrs}$
 Total Investment Cost (based on discharge) = 1045 \$/Kw

Parameter Grouping	Parameter			Parameter Values			Effect on Baseline Investment Cost with Indicated Parameter Value, \$/Kw		Optimistic Parameter Value	Notes
	Name	Symbol	Units	Min	Baseline	Max	Min	Max		
• Redox Converter Parameters + Structural	Channel thickness	τ	cm	0.02	0.5	.2	-3	+13	0.02	--
	Membrane thickness	δ	cm	.002	.01	.015	-52	+34	0.002	--
	Membrane sensitivity	ρ	ohm cm	10	25	100	-41	+273	10	--
	Electrode thickness	a	cm	.005	.01	.05	-1	+4	0.005	--
	Collector thickness	γ_c	cm	.1	.6	.8	-104	+41	0.1	--
	End plate conductor thickness	γ_g	cm	1	1.5	2	-1	0	0.1	--
	Electrode deposit density	ρ_g	gm/cm ³	.4	.5	2	0	+2	0.4	--
	Cell Plastic density	ρ_{cp}	gm/cm ³	.8	.9	2.2	-1	+14	0.8	--
	Collector density	ρ_{cc}	gm/cm ²	1	1.8	3	-54	+80	1.8	--
	Stack installation clearance	$\left(\begin{smallmatrix} \delta_{SW} \\ \delta_{SH} \\ \delta_{SL} \end{smallmatrix} \right)$	cm	(20, 20)	(30, 30)	(40, 40)			20, 20	--
			cm	(10)	(20)	(30)	0	0	10	--
			cm	(20)	(30)	(40)			20	--
+ Cost	Membrane Cost	C_M	\$/m ²	1	9	20	-27	+35	1	--
	Stack fabrication cost	f_m	--	2	2.5	3	-32	+32	2	--
	Cell plastic cost	C_{cp}	\$/kg	0.5	0.57	5	-1	+77	0.5	--
	Collector cost	C_{cc}	\$/kg	1	3.3	10	-85	+245	1	--
	Electrode Cost	C_g	\$/kg	1	2.2	10	0	+2	1	--
	Trailer piping cost	C_{TP}	\$/kw	2.5	5	15	-3	+10	2.5	--
	Trailer busbar cost	C_{TBB}	\$/kw	5	10	20	-6	+10	5	--
	Trailer structurals cost	C_{TS}	\$/kw	2.5	5	15	-3	+10	2.5	--
	Trailer instrument cost	C_{TI}	\$/kw	2.5	5	15	-3	+10	2.5	--
	Trailer installation cost	C_I	\$/kw	15	20	30	-6	+10	15	--
	Power conditioner installation cost	C_{PCI}	\$/kw	15	20	30	-6	+11	15	--

ORIGINAL PAGE IS
OF POOR QUALITY

Notes for Table 3-24

- (1) Varied over range 0.4-1.5 volts. See Figure 3-25.
- (2) Not varied, assumed zero throughout.
- (3) Varied over range 1-3 eq/mole. See Figure 3-25.
- (4) Varied over range 1-5 gm moles/liter. See Figure 3-25.
- (5) Varied over range 0.5-10 \$/kg. See Figure 3-25.
- (6) Varied over range 0.01-0.5 amps/cm². See Figure 3-26.
- (7) Values of η_p adjusted to give:

<u>Level</u>	<u>$a_x a$, cm²</u>	<u>a, cm</u>
Min	400	20
Baseline	1600	40 (Also used for Optimistic Case)
Max	3600	60

- (8) See Figure 3-24 for additional data.
- (9) Varied over range 25-90°C. Cell temperature of 25°C, coupled with 25°C ambient temperature gave thermodynamically impossible heat transfer conditions.

The definition of each of these symbols is given in Tables 3-21 and 3-22 and is also discussed in the Stage 1 Model documentation package. Of course, the magnitude of the cost sensitivity is a function of the specific limiting values assigned for each of the parameters. Comparison of the effect on cost of a fixed percentage change in each parametric variable could also have been made, but the present approach yields more useful information.

Several of the parameters were varied over a wide range. Figure 3-25 shows the effect on cost of the following parameters: reversible cell voltage (v_R), electron transfer number (Z), reactant concentration (C) and reactant cost (C_R). As expected, increasing v_R , Z and C decreased the investment cost. Here, the effective energy density of the Redox couple increases, yielding a smaller, cheaper plant. Additional discussion of this effect is presented below. The results in Figure 3-25 also show that system cost increases lineary with increasing reactant cost.

The effect of large changes in charge current density, i_c , was also explored. As shown in Figure 3-26, there is an optimum value of i_c that results in minimum investment cost. Fortunately, for the base-line parameter values, this occurs at $i_c = 0.1$ amps/cm², the current density assigned as a base-line quantity.

Further analysis of this effect was made by examining the variation of subsystem costs as a function of the charge current density. These results are given in Figure 3-27. As shown, the Redox converter cell (trailer) cost initially decreases as i_c increases. This is caused by the resulting increase in discharge power density, requiring fewer cells for a fixed $P_D = 20$ MW. Eventually, at very high i_c values, the trailer power levels increase to a point where the power-related costs (piping, busbars, structurals, instruments and installation) predominate, and the investment costs for the installed trailer increases. Counter-balancing the initial effect of i_c on the trailer cost, there is a gradual increase in the cost of the remaining subsystems as i_c increases. Here, an effect was seen of increasing flow rate and decreasing system energy storage efficiency (not shown in Figure 3-27) on overall system costs.

The sensitivity analysis was expanded to determine the effect of i_c on costs at several levels of v_R , the reversible cell voltage. A matrix of computer runs was made at $v_R = 0.4$ -1.5 volts and $i_c = 0.02$ -0.5 amps/cm². The results of this analysis are shown in Figure 3-28, which is a map of v_R versus i_c , containing isopleths of constant investment cost. The locus of optimum charge current density is also shown. Optimum i_c increases gradually as v_R increases. Figure 3-28 also shows clearly that lower investment costs, approaching the break-even targets, can be achieved by using Redox couples with high reversible voltage.

Figure 3-25

Effect of Key Parameters on Redox System Investment Cost

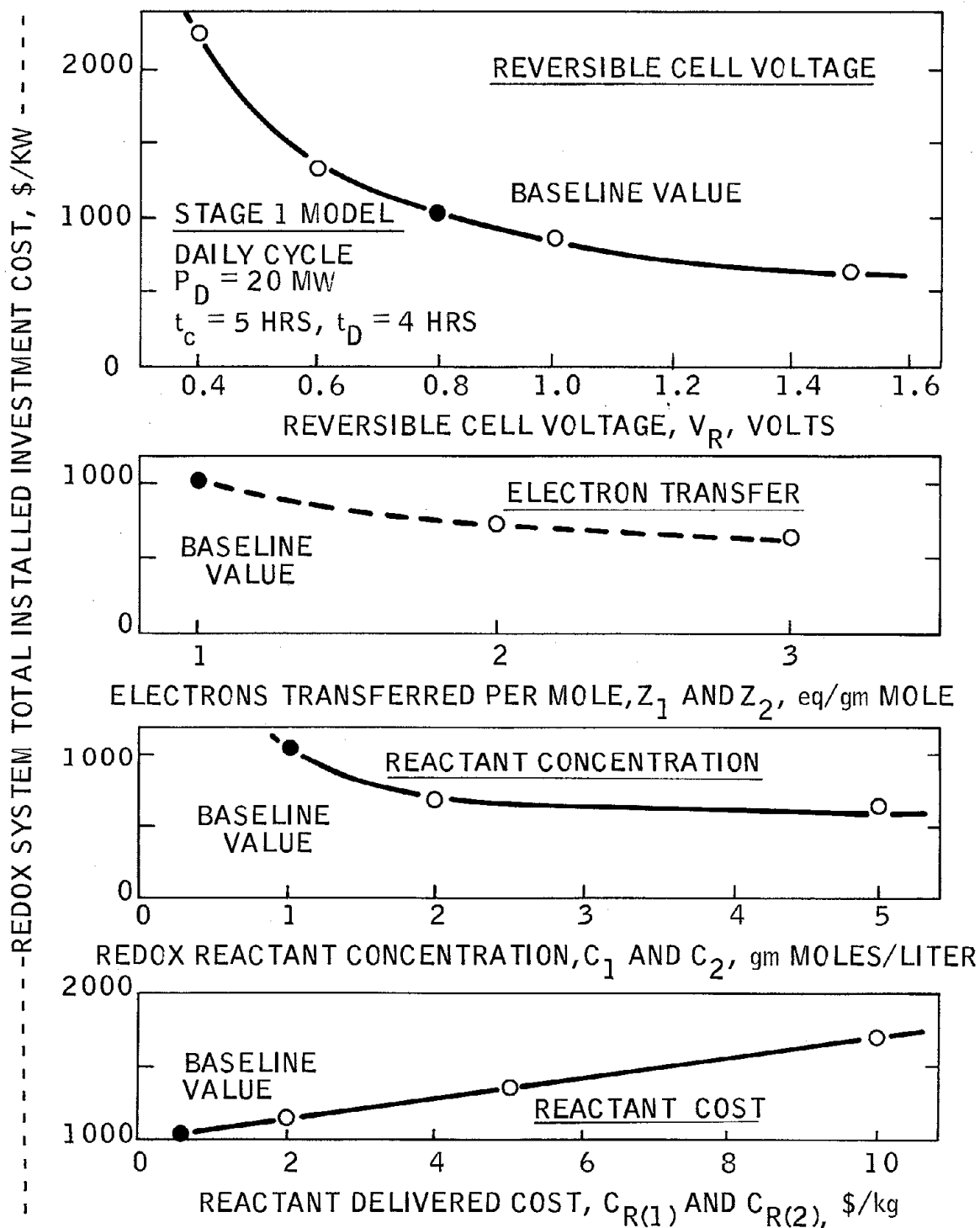


Figure 3-26

Effect of Charge Current Density on Investment Costs

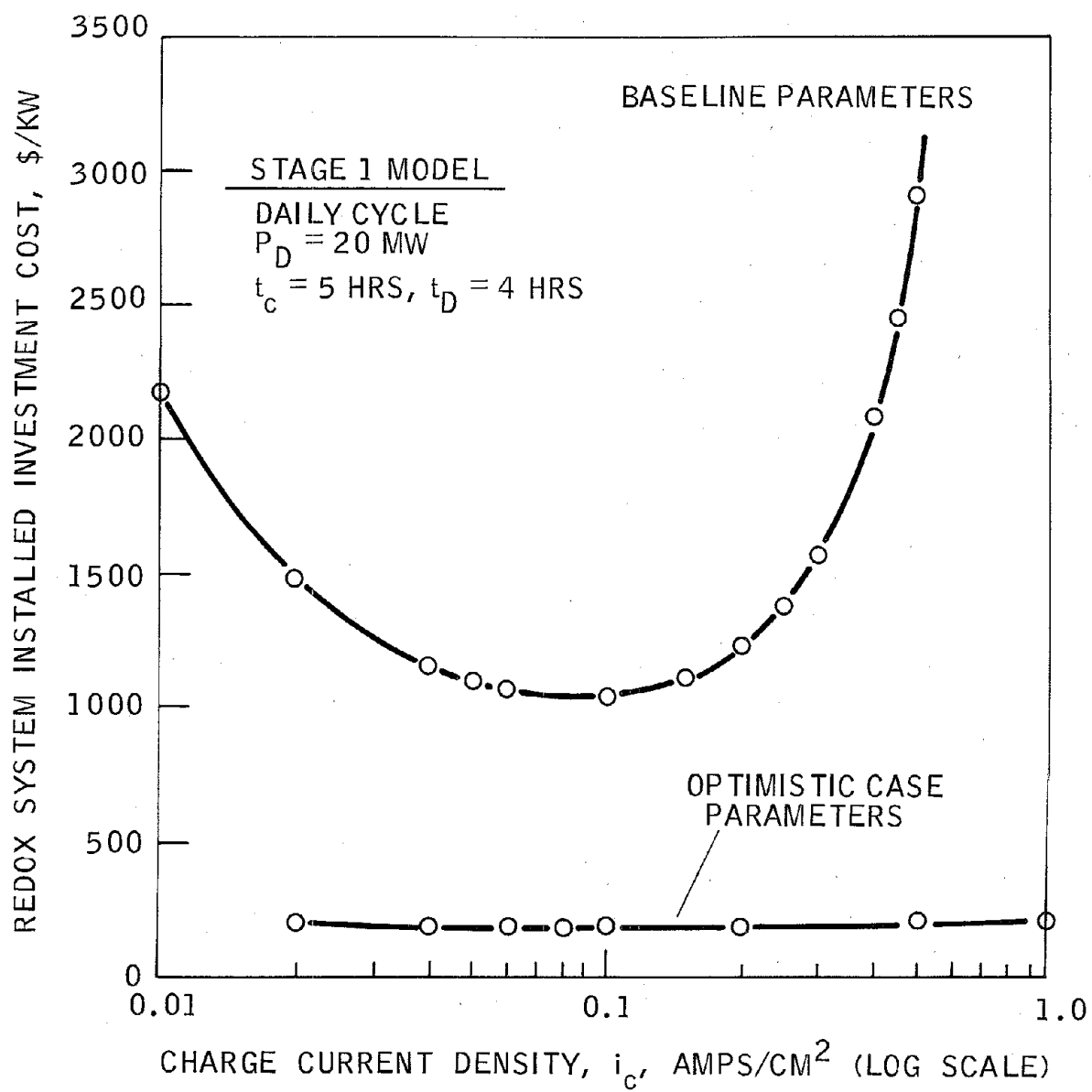


Figure 3-27

Breakdown of Redox System Costs
As a Function of Charge Current Density

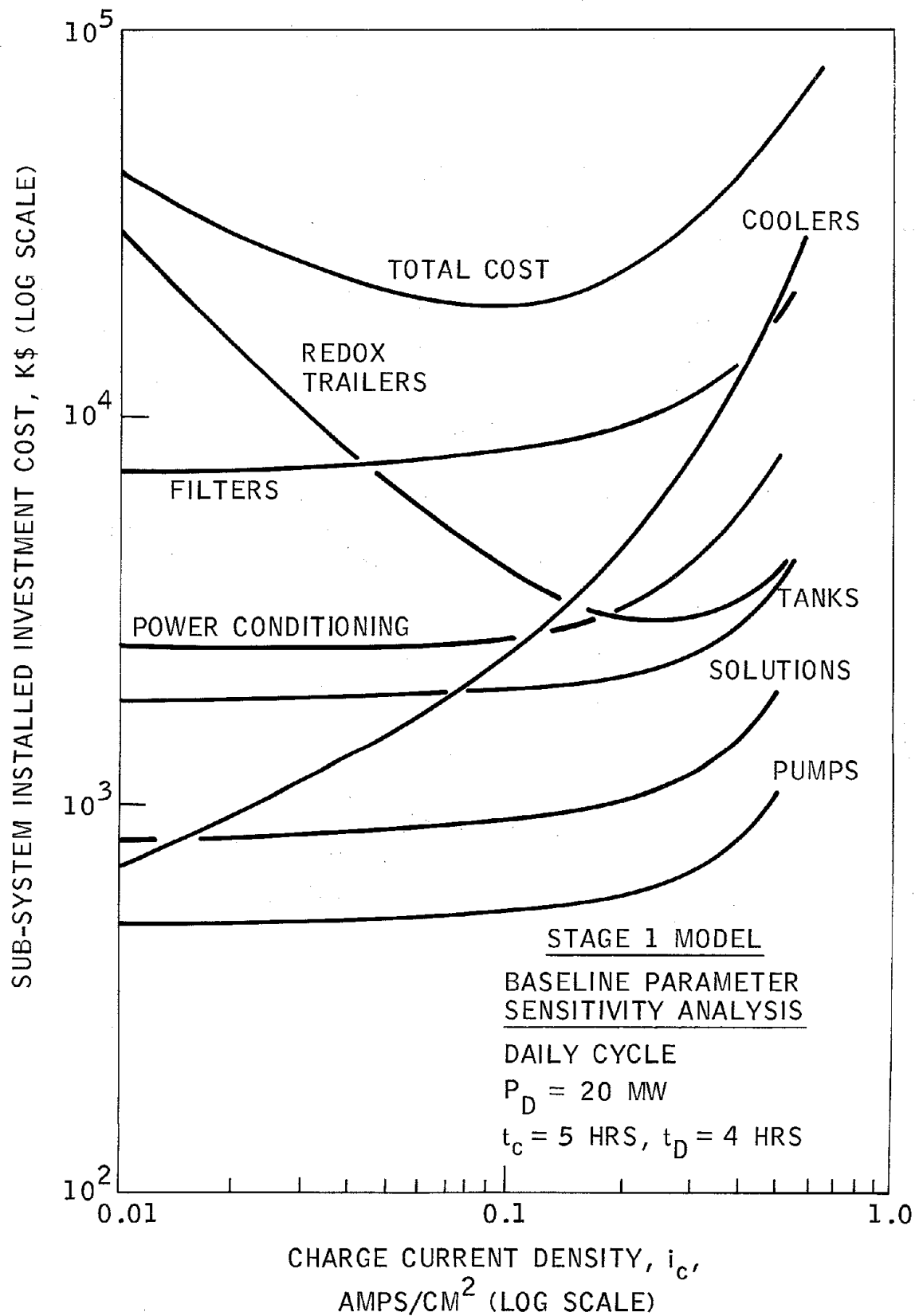
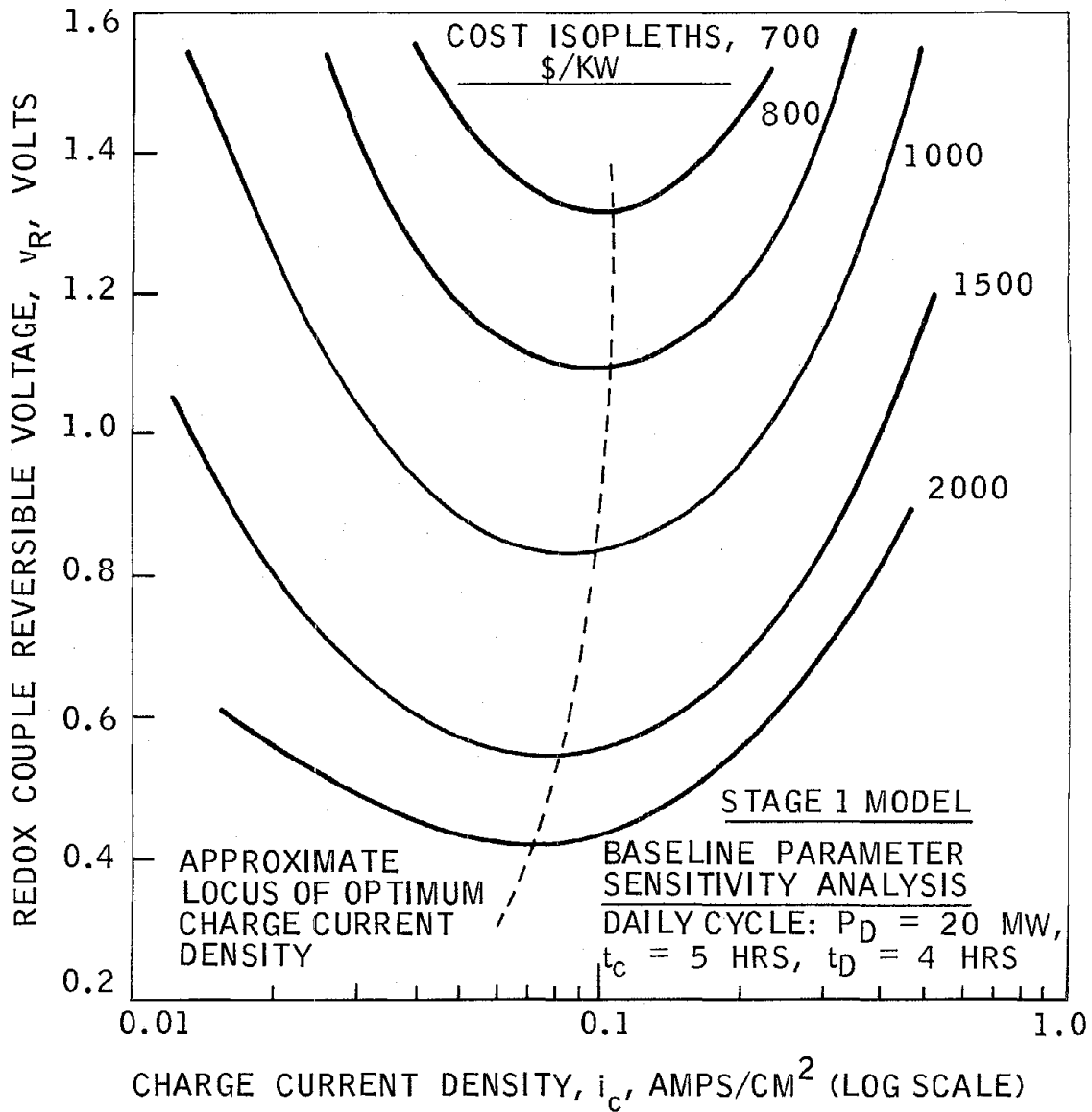


Figure 3-28

Optimum Charge Current Density Varies Slightly With
Reversible Cell Voltage



Lastly, the composite results of the sensitivity analysis were analyzed. This was done by calculating the apparent energy density, WH/liter, of the Redox solutions as the parameters were varied. Here,

$$\text{Apparent Energy Density, WH/l} = \frac{(\mathcal{P}_D - P_{AUX}) t_D 10^3}{(V_1 + V_2)}$$

where: \mathcal{P}_D = AC discharge power, MW
 P_{AUX} = Auxiliary power requirement, MW
 t_D = Discharge time, hrs
 V_1, V_2 = Calculated volume of reactant solutions, k liters

The results, shown in Figure 3-29, indicate the pronounced effect of energy density on system costs. It appears that combinations of Redox couple characteristics and system operating parameters resulting in an apparent energy density greater than 50 WH/l will prove attractive.

An algebraic analysis of the Stage 1 Model was made to define the reactant concentrations (solubility) that are required to achieve 50 WH/l. Using the base-line parameter values, and assuming that the reactant concentrations are equal ($C_1 = C_2 = C$), it was found that couples with equivalence factors (Z_1/Z_2) of 1/1 will give 50 WH/l at concentration levels between 5 and 6 moles/liter. These are clearly achievable values for many couples. The required concentration level is plotted versus the charge/discharge time ratio, t_C/t_D , in Figure 3-30. The effect of increasing the couple equivalence factor is also shown. For example, a couple with $Z_1/Z_2 = 1/3$ would require only 3.5 to 4 molar concentration to achieve 50 WH/l. Again, these should be achievable target levels for Redox couples under study in other phases of NASA's program.

3.3.4.5 Analysis of Weekly Cycle Energy Storage Systems

Analysis of Redox energy storage systems was extended to include weekly cycles, using the Stage 1.5 Model described earlier. Cycles with the following characteristics were evaluated.

- + Discharge power level, $\mathcal{P}_D = 20$ MW (constant throughout cycle)
- + Charge power level, $\mathcal{P}_C = 10-30$ MW (constant throughout cycle)
- + Discharge time profile: 1-11 hrs. on Monday thru Saturday
- + Charge time profile: 5-9 hrs. on Monday thru Saturday
10-24 hrs. on Sunday (maximum available)
- + Base-line parameter values

Figure 3-29

Redox Systems Investment Costs Respond Favorably to Increased Energy Density

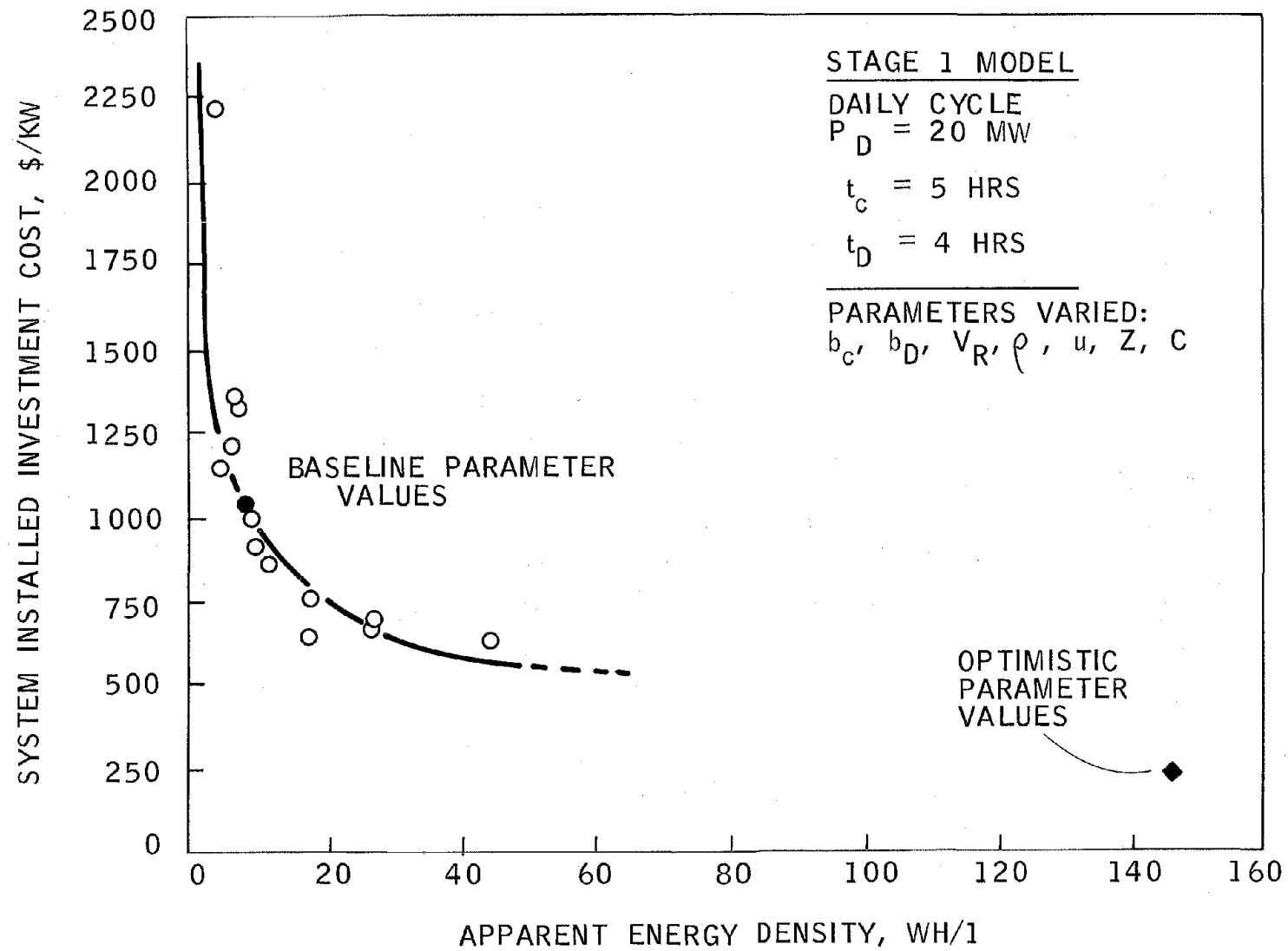
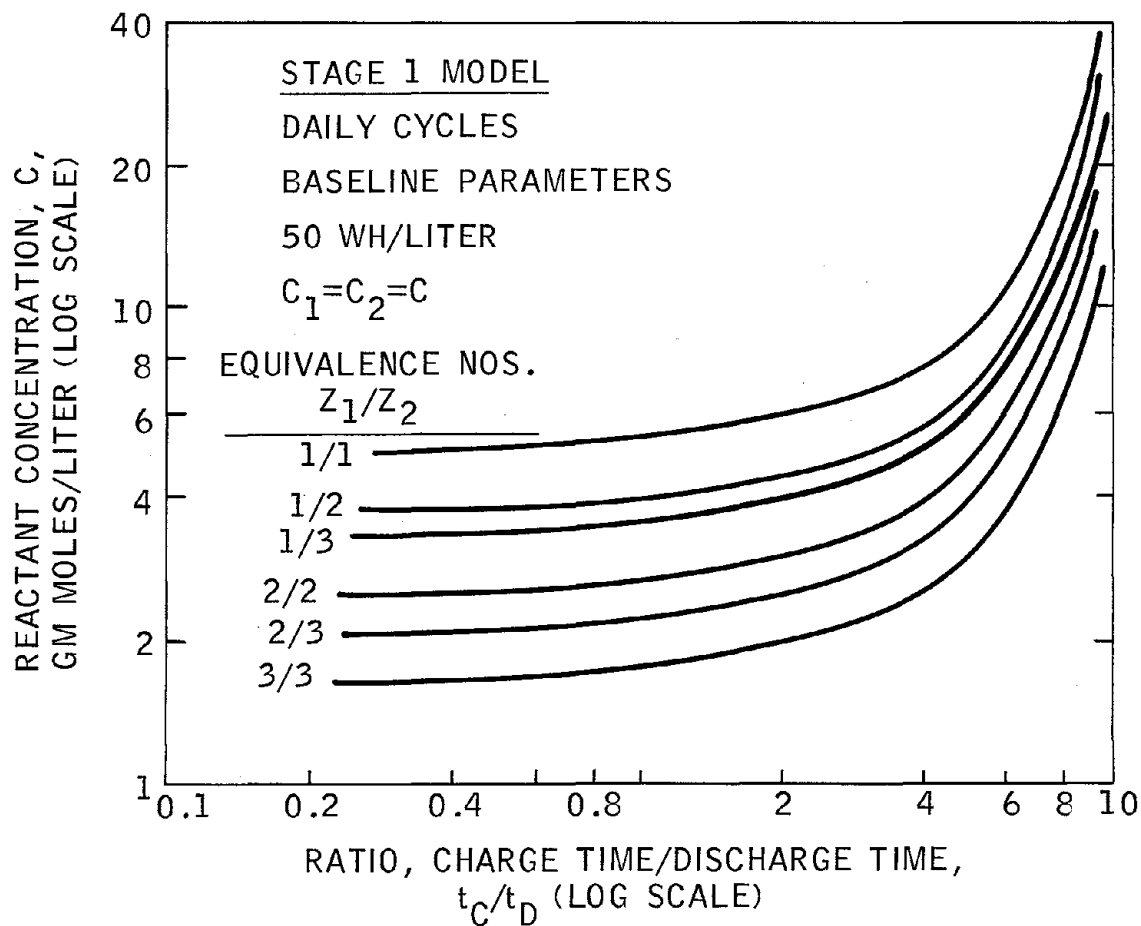


Figure 3-30

Redox Reactant Concentrations
Required to Achieve 50 WH/L Energy Density



The analysis was carried out with a form of the Stage 1.5 Model that truncated the daily charge time to prevent a reactant inventory "build-up". In other words, if less than the available maximum daily charge time was sufficient to restore the solutions to their initial charged condition, the program terminated the charge cycle. This program option also included an optimization sequence, involving a search for a value of charge current density, i_c , that yielded minimum power investment cost, \$/kw.

A number of cycles were found to be thermodynamically impossible. Here, the ratio :

$$\frac{\text{Total Weekly Energy Required to Meet Discharge P-t Profile}}{\text{Total Weekly Energy Available from Charge P-t Profile}}$$

exceeded the maximum system efficiency, calculated using the base-line parameters in the Stage 1 Model. It will be recalled that:

$$\text{Efficiency (ex-auxiliary power)} = \frac{v_D}{v_C} E_I E_R E_{FD} E_{FC}$$

where: v_D, v_C = Discharge and charge voltage

E_I, E_R = Inverter and rectifier efficiency

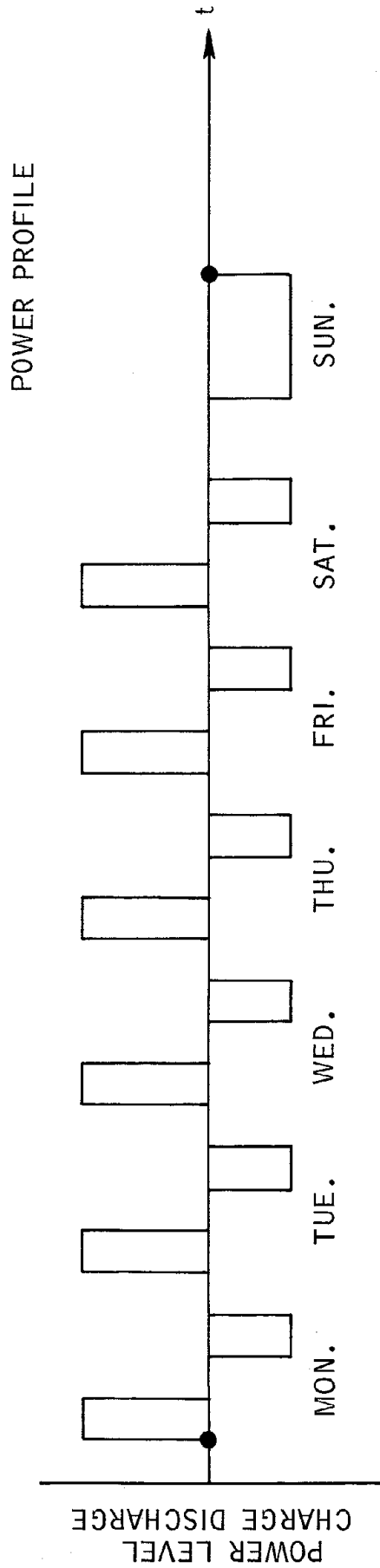
E_{FD}, E_{FC} = Faradaic efficiency for discharge and charge reactions.

In the limit, as $i_c \rightarrow 0$, v_C and $v_D \rightarrow v_R$, and the maximum attainable efficiency is given by the efficiency term product.

The Stage 1.5 Model uses exactly the same component sizing and costing routines as the Stage 1 Model to obtain the total installed cost of each weekly cycle system. This cost, divided the (constant) discharge power level, is defined as the power investment cost, \$/kw. Conversion of this cost to an energy-related basis, \$/kwh, is less straight-forward. Here, the maximum discharge time, $(t_D)_{\max}$ was calculated, equivalent to the length of time a fully charged inventory could be run to supply the required discharge power level. This hypothetical $(t_D)_{\max}$ was used to calculate the energy investment costs for the weekly cycles. Of course, for the daily cycle analysis, t_D and $(t_D)_{\max}$ are the same. Figure 3-31 shows a hypothetical weekly cycle and reactant inventory profile. An illustrative value of $(t_D)_{\max}$ is shown for further clarification.

Power investment costs for composite weekly and daily cycles are plotted versus discharge time parameters in Figure 3-32. The break-even cost target range for advanced batteries is included in this figure. As indicated, weekly cycles provide a very attractive application for the Redox battery concept. Although the base-line parameter systems continue to be expensive, systems having maximum discharge times exceeding 18 hrs. begin to fall within the cost target range.

Figure 3-31
A Hypothetical Weekly Cycle



INVENTORY PROFILE

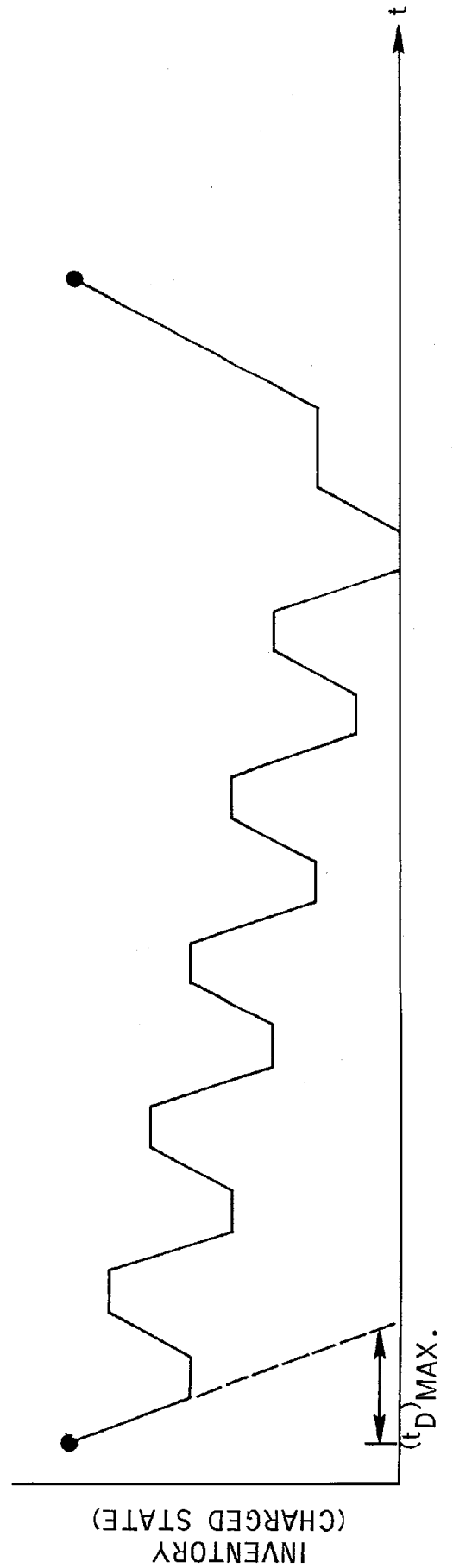
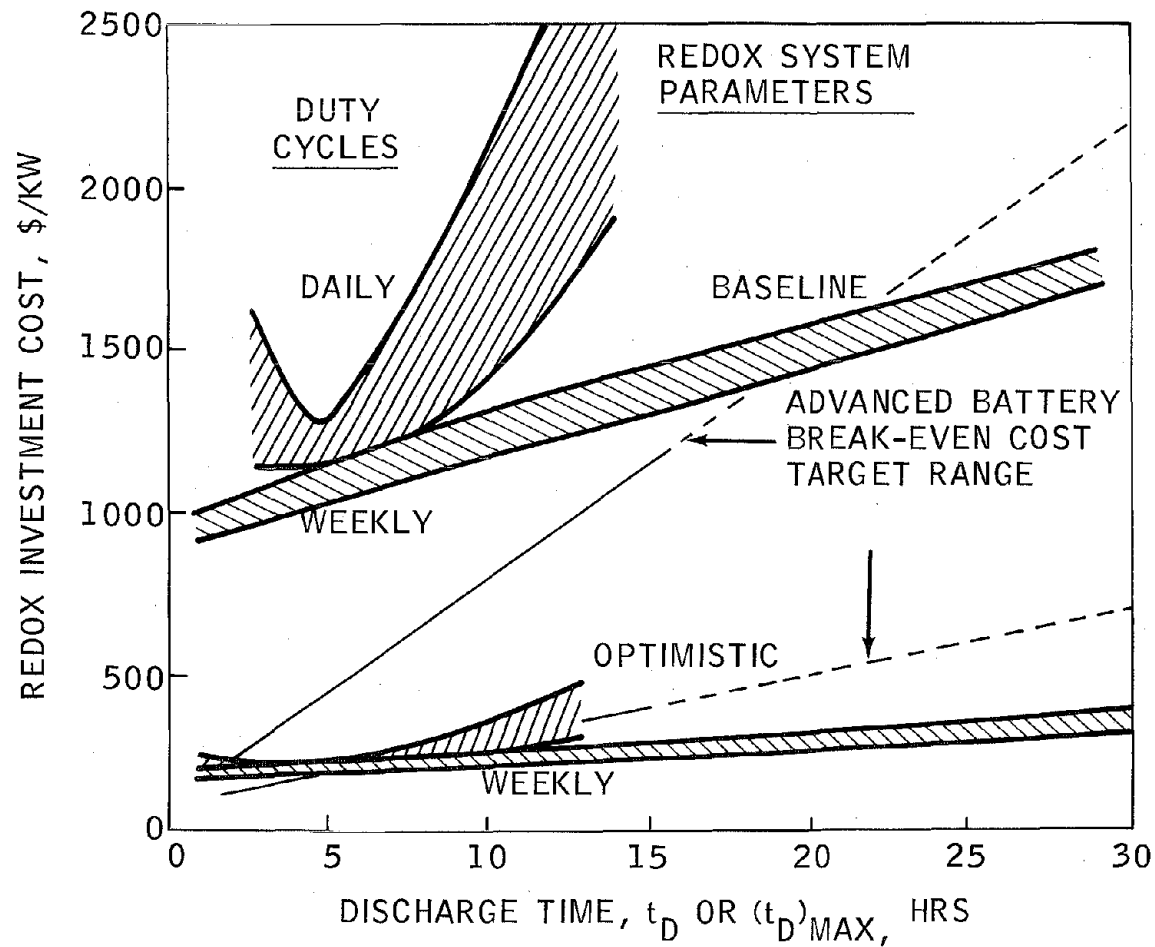


Figure 3-32

Considerable Opportunity Exists For Optimizing
Daily and Weekly Redox Systems

$P_D = 20 \text{ MW}$ $P_c = 10\text{-}30 \text{ MW}$ $t_c = 5\text{-}9 \text{ HRS DAILY} + \text{SUNDAY}$



Weekly cycle energy investment costs for the Redox system were compared with conventional and advanced battery cost projections. As shown in Figure 3-33, the weekly cycle Redox systems compare favorably with other battery systems. The conservative base-line parameter cases have lower energy investment costs than lead-acid batteries for maximum discharge times exceeding 18-24 hours. Correspondingly, the optimistic parameter Redox systems appear less costly than projected advanced batteries for discharge times exceeding 5-6 hours.

This analysis led to an exploration of the possibility of defining systems optimized on the basis of energy investment costs, \$/kwh, rather than power-related costs, \$/kw. A modification of the Stage 1.5 Model was developed to do this. Rerunning the weekly cycle cases with this new program option gave some interesting results. A typical case is shown in Table 3-25, which compares the analysis of a given power-time profile using both program options. As shown, substantial differences in \$/kw and \$/kwh were obtained. Examination of the program output showed that the \$/kw optimization option resulted in lower current density operation, with high efficiency and minimum use of Sunday power for recharging. The \$/kwh optimization gave a low cycle efficiency, higher absolute investment cost, but, as expected, much lower relative energy investment cost.

The attractiveness of either option would depend on specific electric utility operational requirements. At this point, the major significance of this analysis is to show the considerable design flexibility possible with the Redox energy storage concept.

A final modification was made to the Stage 1.5 Model to assess the value of allowing a daily "overcharge", early in the week, to help overcome long late-week discharge demands. These demands could occur with "asymmetric" discharge time profiles.

Several asymmetric discharge time profiles were analyzed using this modified program. A typical case is displayed in Figure 3-34 and Table 3-26. Analysis of the same profile with the original (truncated discharge time) version of the Stage 1.5 Model is also shown. Figure 3-34 shows the inventory profile, during the week, of reactant 1 in the charged state. Note that a point of "zero" inventory occurs in both model options. Truncating the charge cycles early in the week to match the early discharge cycles shifts this "zero" point to Friday afternoon, at the end of the maximum discharge period. Permitting "overcharge" early in the week shifts the point of "zero" inventory. Both options are technically acceptable and result in balanced, steady-state operation. These operations, however, differ from each other, as shown by the data in Table 3-26. Permitting temporary "overcharge" resulted in lower current density operation, higher efficiency, slightly higher overall power investment costs and lower energy investment costs. Again, the adaptability of the Redox concept was demonstrated.

Both program options were also used to analyze a symmetric discharge time profile case. As shown in Figure 3-35 and Table 3-27, substantial differences in energy-related costs were obtained. It appears that a family of solutions exists that can satisfy the technical requirements of an imposed power-time profile or cycle. It is not clear, at this time, what the best "figure-of-merit" should be for selecting an "optimum" case from this family.

Figure 3-33

Energy Investment Costs for Batteries in Weekly Storage Cycles

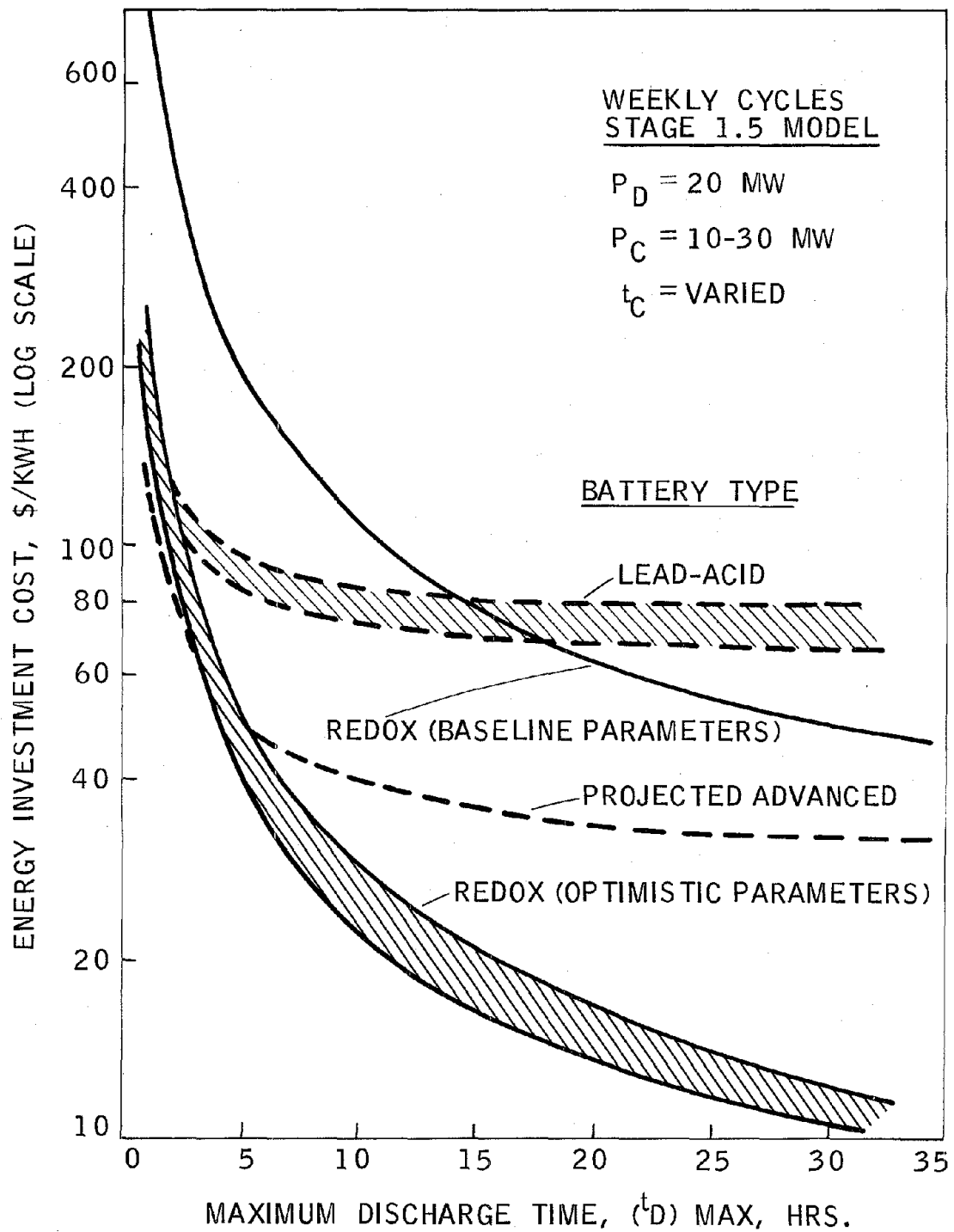


Table 3-25

Comparison of Weekly Cycle Analysis Using Stage 1.5 Model
With Different Optimization Parameters

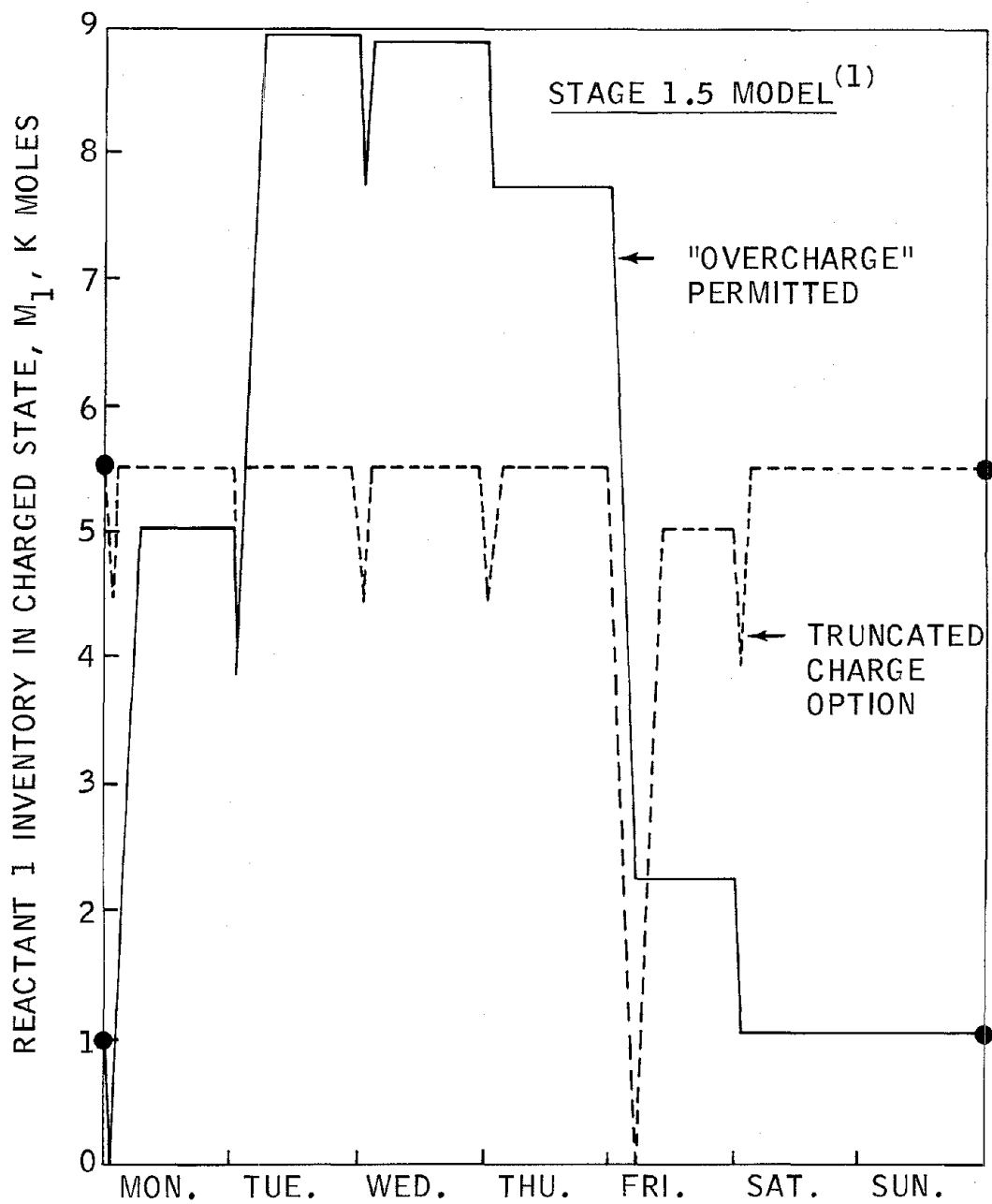
Cycle Characteristics ⁽¹⁾	Optimization Parameter	
	<u>\$/kw</u>	<u>\$/kwh</u>
Charge current density, i_C	0.076	0.205
Discharge current density, i_D	0.078	0.302
Number of Redox trailers, N_T	24	8
Efficiency (incl. aux. power), %	73.1	49.4
Maximum discharge time, $(t_D)_{max}$, hrs	5.6	13.0
Component Investment Cost, K\$		
Tankage	2519	5951
Pumps	516	629
Filters	7718	10311
Coolers	1866	5923
Redox Trailers	5166	2438
Power Conditioning	3066	3066
Reactants	<u>1206</u>	<u>3628</u>
Total	22057	31946
\$/kw	1103	1597
\$/kwh	197	123

(1) $P_D = 20$ mw, $P_C = 25$ mw. Time profiles:

	<u>Mon.</u>	<u>Tue.</u>	<u>Wed.</u>	<u>Thu.</u>	<u>Fri.</u>	<u>Sat.</u>	<u>Sun.</u>
Required t_D	5	5	5	5	5	5	0
Available t_C	5	5	5	5	5	5	24
Actual t_C (\$/kw)	5	5	5	5	5	5	0.7
Actual t_C (\$/kwh)	5	5	5	5	5	5	14.2

Figure 3-34

Reactant Inventory Profiles for Asymmetric Discharge Time Case



(1) See Table 3-26 for details.

Table 3-26

Effect of Charge Options on Analysis
Of Asymmetric Discharge Time Profiles

Cycle Characteristics(1)	Stage 1.5 Model Option(2)	
	Option A ("Overcharge" Possible)	Option B (Truncated Charge)
Charge current density, i_C	0.113	0.106
Discharge current density, i_D	0.125	0.115
Number of Redox trailers, N_T	16	17
Efficiency (incl. aux, power), %	67.2	68.4
$(t_D)_{max}$, hrs.	8.0	5.0
Component Investment Cost, k\$		
Tankage	3458	2374
Pumps	535	531
Filters	8153	8060
Coolers	2428	2319
Redox Trailers	3765	3950
Power Conditioning	3066	3066
Reactants	<u>1810</u>	<u>1118</u>
	Total	21418
	\$/k2	1071
	\$/kwh	214

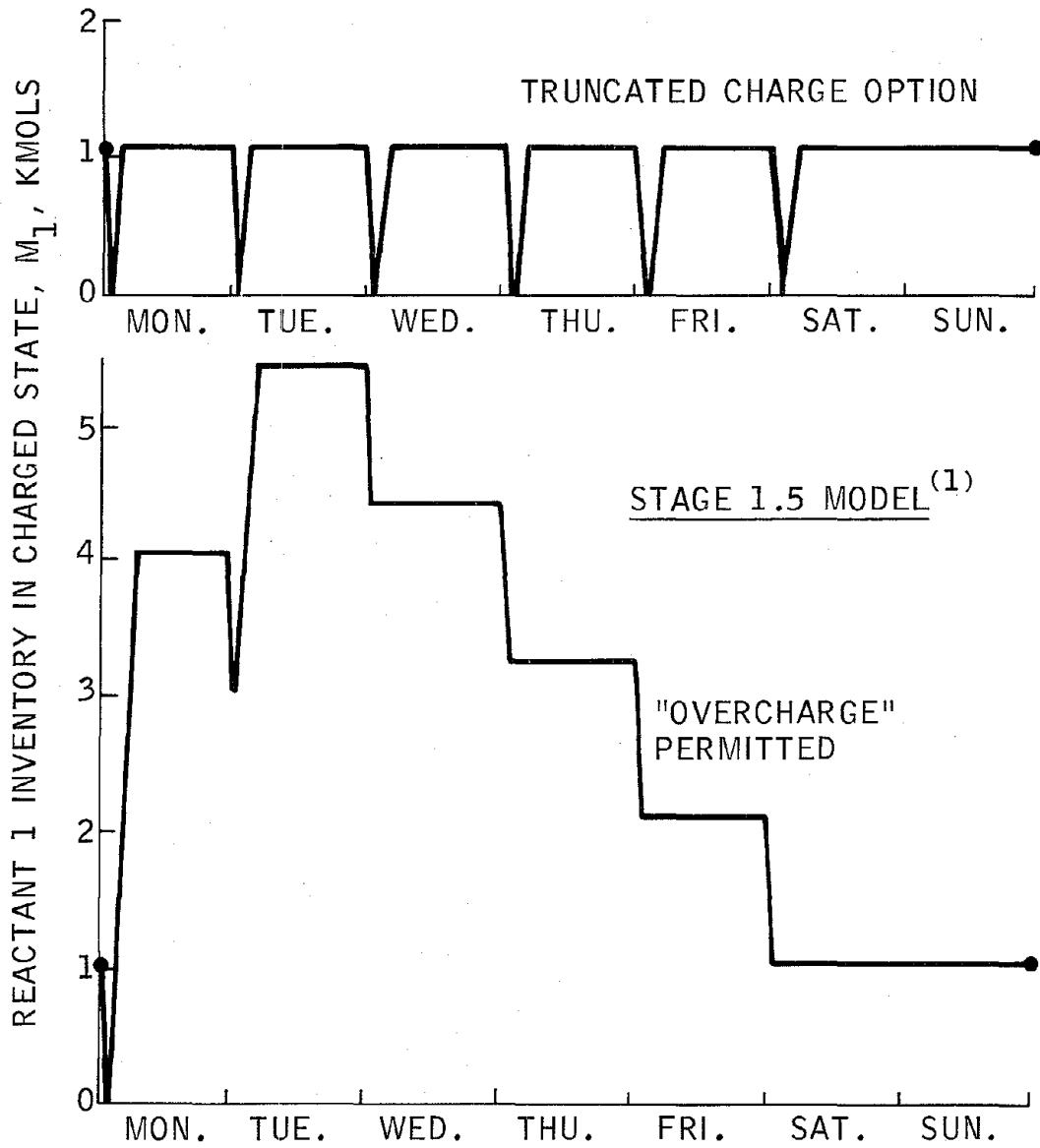
(1) $P_D = 20$ mw, $P_C = 25$ mw. Time Profiles:

	Mon.	Tue.	Wed.	Thu.	Fri.	Sat.	Sun.
Required t_D	1	1	1	1	5	1	0
Available t_C	5	5	5	5	5	5	24
Actual $t_C(A)$	5	5	1.1	0	0	0	0
Actual $t_C(B)$	1.1	1.1	1.1	1.1	5.0	1.6	0

(2) Optimized on basis of \$/kw

Figure 3-35

Reactant Inventory Profiles for Symmetric Discharge Time Case



(1) See Table 3-27 for details.

Table 3-27

Effect of Charge Options on Analysis of Symmetric
Discharge Time Profiles

Cycle Characteristics ⁽¹⁾	Stage 1.5 Model Option ⁽²⁾	
	Option A ("Overcharge" Possible)	Option B (Truncated Charge)
Charge current density, i_C	0.084	0.087
Discharge current density, i_D	0.112	0.118
Number of Redox Trailers, N_T	17	16
Efficiency (incl. aux. power), %	69.4	68.9
$(t_D)_{max}$, hrs.	5.0	1.0
Component Investment Cost, K\$		
Tankage	2368	866
Pumps	530	532
Filters	8031	8081
Coolers	2283	2344
Redox Trailers	3898	3779
Power Conditioning	2582	2582
Reactants	<u>1115</u>	<u>222</u>
Total	20807	18406
	\$/kw	920
	\$/kwh	920

(1) $P_D = 20$ mw, $P_C = 20$ mw. Time profiles:

	<u>Mon.</u>	<u>Tue.</u>	<u>Wed.</u>	<u>Thu.</u>	<u>Fri.</u>	<u>Sat.</u>	<u>Sun.</u>
Required t_D	1	1	1	1	1	1	0
Available t_C	5	5	5	5	5	5	24
Actual $t_C(A)$	5	3	0	0	0	0	0
Actual $t_C(B)$	1.3	1.3	1.3	1.3	1.3	1.3	0

(2) Optimized on basis of \$/kw.

3.3.4.6 Cost Reduction Opportunities for Redox Energy Storage Systems

The preceding analyses have shown that the Redox battery system can be cost-competitive in a number of utility energy storage applications, if certain combinations of system parameter values can be achieved. The following discussion will focus on likely areas of improvement, leading to reduced sub-system and total system investment costs. Emphasis is placed on schemes for reducing the cost of the auxiliary sub-sections.

- Redox Couple Selection

The sensitivity analysis, discussed earlier, showed that the apparent energy density, WH/liter, of the Redox couple strongly influenced the total system cost. More energetic couples required lower tank volumes, reactant inventory, and solution flow rates. All of these factors contributed to lower investment costs. Additional analysis was carried out to better define the effect of energy density on costs. A series of computer runs was made varying only those parameters that play a major role in defining the Redox couple apparent energy density. These parameters include the reversible voltage, the number of equivalents/mole and the reactant concentrations. All remaining parameters, including the cost factors, were kept constant at their base-line value. The results of this analysis are shown in Figures 3-36 and 3-37. Here, increasing the energy density to 100 WH/liter still leaves the investment cost for the daily cycle somewhat off-target, 500 \$/kw versus 187-373 \$/Kw. On the other hand, the weekly cycle begins to fall into the target cost zone at about 60-80 WH/liter.

Clearly, the search for improved Redox couples is desirable and should be encouraged. Improvements, however, are still required to develop lower cost process flow plans and optimized sub-systems.

This analysis was restricted to the key electrochemical parameters. Naturally, the cost and dynamic electrochemical performance (polarization effects, reversibility, stability, faradaic efficiency, etc.) of the couples must also be considered. These factors require experimental determination.

- Tankage

The computational models of the Redox system assumed that corrosive supporting electrolytes would be used. Consequently, a conservative, lined-tank approach was chosen for solution storage. Cost analysis indicated little economy of scale for large-scale tanks.

Figure 3-36

Improved Redox Couples Help, But Additional
System Cost Reduction Is Needed To Meet Daily Cycle Targets

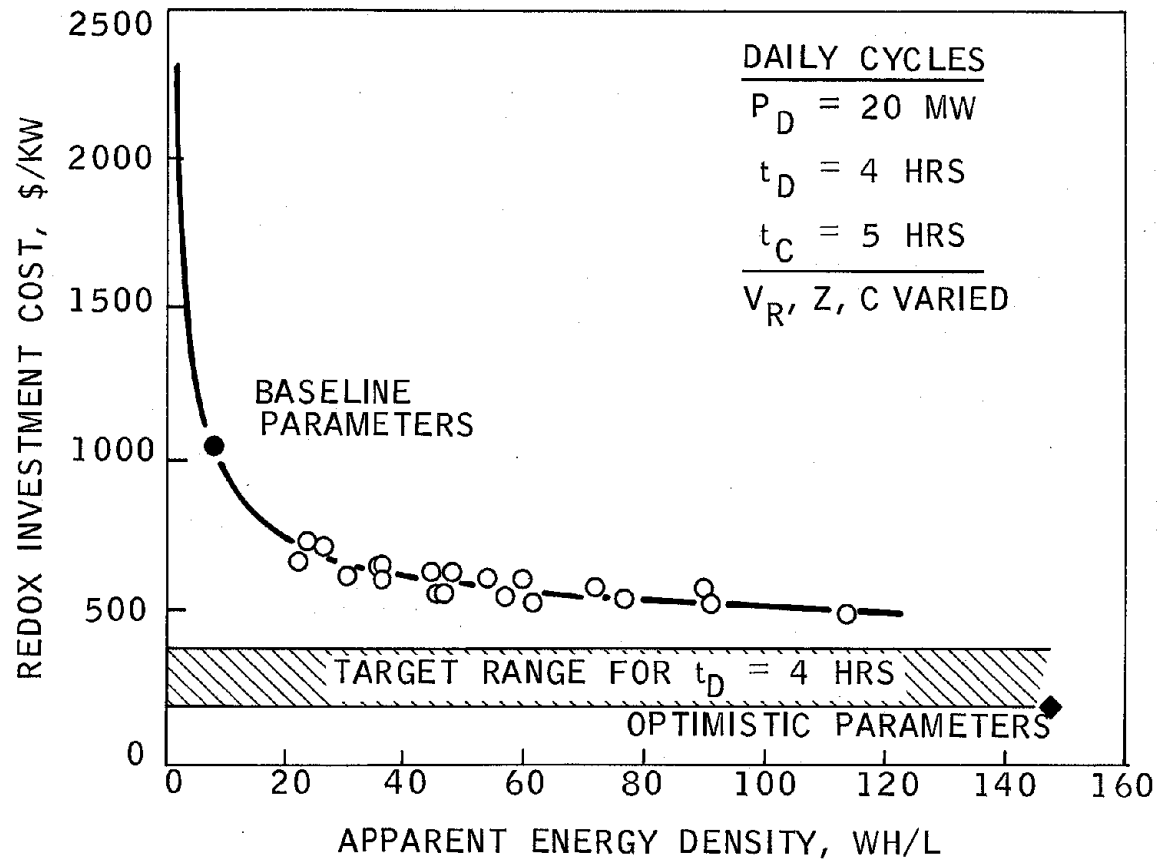
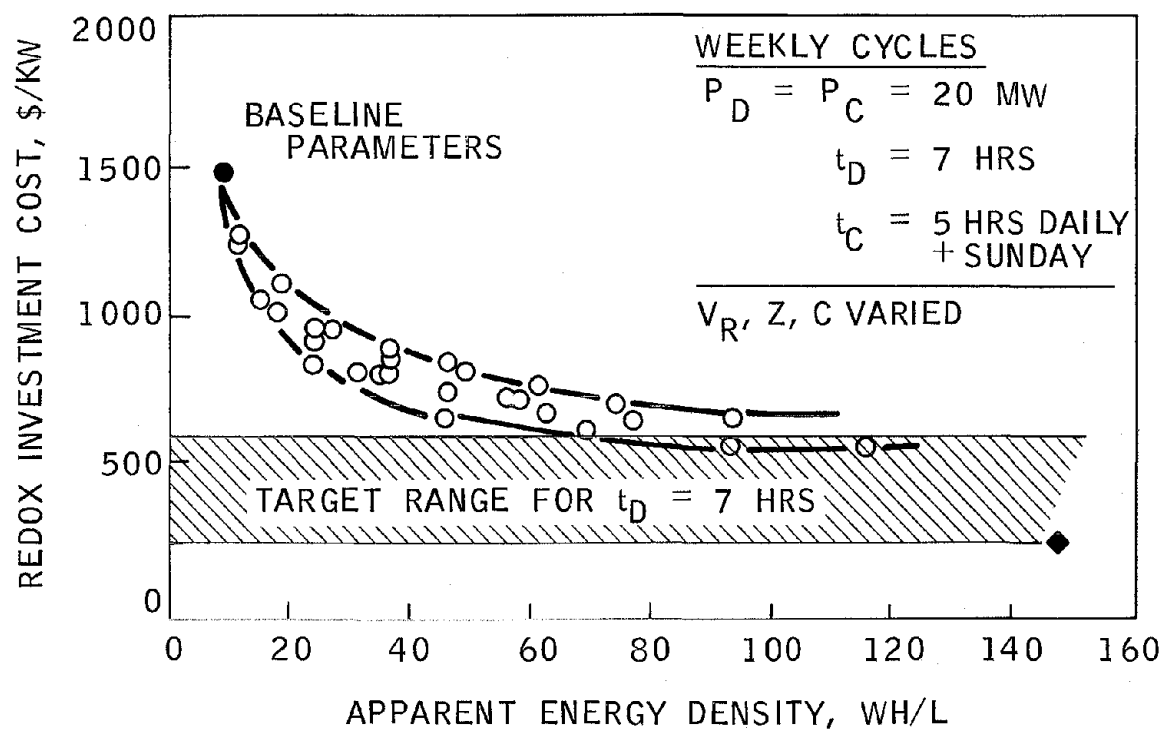


Figure 3-37

Weekly Cycle Targets Are Closer, Especially
With Improved Redox Couples



The upper limit of conventional steel tank volume is approaching the one million barrel level, for petroleum products. Such tanks, if they could be lined safely, could be useful for high power level weekly cycle storage systems. Installed costs for these tanks, however, may remain relatively high.

Alternative approaches could be considered. In-ground, concrete tanks, perhaps lined or surface-impregnated, might be suitable. However, estimating the cost of these tanks would be quite difficult, in the general case. In-ground structure costs are very sensitive to site-specific factors, such as ground quality and hardness and water table.

All plastic or reinforced fiberglass tanks might be useful for smaller stored volumes. Here, too, field-erection costs might be excessive, if labor requirements are high. The use of manifolded plastic pipe was judged too expensive.

A potentially attractive tankage concept was uncovered, in the form of flexible bladders, made of corrosion-resistant rubber (57). These factory-fabricated bladders could be installed with minimal weather protection. Maximum available bladder size was not established. Another variation of this approach involves the spray-coating of a concrete surface over inflated structures or air bubbles (58, 59). These approaches should be studied further. Opportunities also may exist for minimizing the cost of the plastic spillwall liner. Some protective lining would probably be required, based on environmental factors, but lower cost solutions may exist.

- Pumps

The computer models assume the use of corrosion-resistant pumps having high discharge pressure rating (300^+ psig). This limited the maximum pump size to about 6200 gpm, requiring the use of multiple pump assemblies for high solution flow rates. Larger pumps, showing some economy of scale, could be used if the discharge pressure requirements were reduced. It would require a complete system pressure balance analysis, through each reactant loop, to specify suitable pump locations and discharge pressure ratings. A general solution to this problem was beyond the scope of the Redox modelling effort.

- Piping

Piping costs were relatively low in the Redox systems studied. The use of lined-pipe was assumed. Switching to an all-plastic pipe system might reduce the piping material cost, but field erection labor costs would increase. Shorter sections of plastic pipe are used, to compensate for thermal expansion effects. Flexible hosing may be a possibility for smaller storage systems.

- Heat Exchangers (Coolers)

Opportunities for heat exchanger cost reduction may be limited to exploring optimized system operating parameters. Here, trade-off studies involving design point inefficiencies and flow rates are required. Interestingly, the search for Redox couples that are active at low temperature may be counter-productive, if this reduces the available ΔT driving force for the heat exchanger section. Lower temperature may be desirable from a systems corrosion standpoint, but excursions to higher temperature should be permitted.

The extent of self-cooling on stand in the storage tanks was not assessed. Clearly, the heat exchanger section must be sized for the worst-case conditions, probably hot summer afternoons, when utility peak load demands are high.

- Power Conditioning

As indicated earlier, the power conditioning section costs were based on a study reported by Westinghouse. These costs appear higher than earlier literature estimates, and future cost reduction might be expected. Cross-comparisons between Redox systems costs and available advanced battery costs should be normalized to reflect the same power conditioning cost basis. The operating voltage level is a key parameter here. Redox systems may be limited to low voltage levels, if parasitic shortage current losses become excessive.

- Redox Cells

The Stage 1 and 1.5 models used a conservative Redox cell design. Substantial reductions in cost should be possible, using optimized thinner cell designs. The base-line parameters assumed the use of inexpensive polypropylene, combined with more expensive graphite conductive structures. Other potential materials and designs should be explored.

- Filters

Major cost reduction should be possible in the filter sub-section. As discussed earlier, approaches here include the use of in-line porous metal or plastic filters or strainers and, perhaps, large-scale sand bed filters. Identification and development of alternatives to the filter cartridge assemblies used in the computer model simulations is a critical area, requiring further study. Final solution of the filter problem may require additional detailed design studies on a specific Redox battery system, including complete flow balance and pressure drop analysis of the circulating reactant solutions. For these studies to be meaningful, a fixed Redox cell, stack and trailer geometry must be assumed, based on preliminary trade-off studies with specific achievable Redox couple characteristics.

Cost reduction scenarios can be projected, based on the expected results of sub-system design and optimization studies. Based on the foregoing discussion, anticipated cost reduction factors were estimated for each Redox battery sub-system. Moderate and substantial levels of cost reduction were assumed, as shown in Table 3-28. No reduction in reactant cost from the base

Table 3-28

Expected Levels of Sub-System Cost Reduction Factors

<u>Redox Battery Sub-System</u>	<u>Expected Cost Reduction Factors</u>	
	<u>Moderate Level</u>	<u>Substantial Level</u>
Tankage	0.9	0.7
Pump	0.9	0.8
Filter	0.5	0.3
Heat Exchanger	1.0	0.8
Redox Trailer Assembly	0.8	0.7
Power Conditioning	0.7	0.7
Reactant Supply	1.0	1.0

line levels was assumed, but parametric variations could be carried out to establish the sensitivity of optimized Redox battery system cost to varying reactant cost.

These cost reduction factors were applied to several hypothetical Redox battery systems, analyzed earlier during the discussion of Redox couple apparent energy density. Typical daily and weekly cycles were included. The results are given in Tables 3-29 and 3-30 and Figures 3-38 and 3-39. As indicated, lower Redox couple energy density levels are now required to meet the upper cost target limit for the weekly cycle. Costs for the daily cycle application remain somewhat high.

In summary, a number of pathways exist for reducing the cost of Redox energy storage systems projected using the Stage 1 and 1.5 model analysis. These models remain useful tools to focus attention on potential problem areas.

Insufficient time was available to carry out a Redox systems study using the Stage 2 Model. Initial results from this more advanced model emphasized the strong interactions among Redox cell performance and hydrodynamic and mass transfer factors. These results indicate that use of the Stage 1 Model time-averaged performance parameters may have seen quite optimistic. The preliminary findings are discussed further in Appendix 6. Clearly, additional effort is required to search for optimal parameter combinations, using the Stage 2 Model to confirm the systems conclusions reached above.

Table 3-29

Projected Cost Reduction for Daily Cycle Redox Battery System

Case No. (1)	-----1-----			-----2-----			-----3-----			-----4-----		
Redox Couple Energy Density WH/L	8.65 ⁽⁴⁾			35.5			57.2			114.7		
Sub-System Installed Cost at Indicated Factor Reduction Level, k\$	<u>Base-</u> <u>line</u>	<u>Moderate</u>	<u>Substan-</u> <u>tial</u>	<u>Base-</u> <u>line</u>	<u>Moderate</u>	<u>Substan-</u> <u>tial</u>	<u>Base-</u> <u>line</u>	<u>Moderate</u>	<u>Substan-</u> <u>tial</u>	<u>Base-</u> <u>line</u>	<u>Moderate</u>	<u>Substan-</u> <u>tial</u>
Tankage	2010	1809	1407	870	783	609	663	597	464	445	400	312
Pumps	535	482	428	205	184	164	166	149	133	131	118	105
Filters	8153	4076	2446	1999	1000	600	1249	624	375	626	313	188
Heat Exchangers	2429	2429	1943	2520	2520	2016	2261	2261	1809	2477	2477	1982
Redox Trailers	4163	3330	2914	4163	3330	2914	3457	2766	2419	3457	2766	2419
Power Conditioning	2694	1885	1885	2693	1885	1885	2582	1807	1807	2582	1807	1807
Reactants	<u>904</u>	<u>904</u>	<u>904</u>	<u>401</u>	<u>401</u>	<u>401</u>	<u>577</u>	<u>577</u>	<u>577</u>	<u>287</u>	<u>287</u>	<u>287</u>
Total, k\$	20888	14916	11927	12851	11181	8589	10955	8781	7584	10005	8168	7100
\$/kw ⁽²⁾	1044	746	596	643	559	429	548	439	379	500	408	355
\$/kWh ⁽³⁾	261	186	149	161	140	107	137	110	95	125	102	89

(1) Daily cycle: Discharge power = 20 MW; Discharge time = 4 hrs.; Charge time = 5 hrs.; Typical cases with various combinations of Z (1,2); C (1, 2, 5); V_R (0.8, 1.0).

(2) Based on discharge power level.

(3) Based on discharge time

(4) Base-line parameter value

Table 3-30

Projected Cost Reduction for Weekly Cycle Redox Battery System

Case No. (1)	----- 1 -----			----- 2 -----			----- 3 -----			----- 4 -----		
Redox Couple Energy Density, WH/L 8.99 ⁽⁴⁾	22.5			23.1 22.4			69.6 22.5			116.3 22.5		
(t _D) _{max} , hrs.	22.5			22.4			22.5			22.5		
Sub-System Installed Cost at Indicated Factor Level, k\$ Reduction	<u>Base-</u> <u>line</u>	<u>Moderate</u>	<u>Substan-</u> <u>tial</u>	<u>Base-</u> <u>line</u>	<u>Moderate</u>	<u>Substan-</u> <u>tial</u>	<u>Base-</u> <u>line</u>	<u>Moderate</u>	<u>Substan-</u> <u>tial</u>	<u>Base-</u> <u>line</u>	<u>Moderate</u>	<u>Substan-</u> <u>tial</u>
Tankage	7501	6751	5251	3643	3279	2550	1601	1441	1121	1193	1074	835
Pumps	516	464	413	260	234	208	154	139	123	130	117	104
Filters	7786	3893	2336	3054	1527	916	1028	514	308	618	309	185
Heat Exchangers	1964	1964	1571	1944	1944	1555	2106	2106	1685	2232	2232	1786
Redox Trailers	4717	3774	3302	3457	2766	2420	3324	2659	2327	3338	2670	2337
Power Conditioning	2582	1807	1807	2582	1807	1807	2582	1807	1807	2582	1807	1807
Reactants	<u>4878</u>	<u>4878</u>	<u>4878</u>	<u>1934</u>	<u>1934</u>	<u>1934</u>	<u>1663</u>	<u>1663</u>	<u>1663</u>	<u>1602</u>	<u>1602</u>	<u>1602</u>
Total, k\$	29947	23531	19558	16874	13491	11390	12458	10329	9034	11695	9811	8656
\$/kw ⁽²⁾	1497	1177	978	844	675	570	623	516	452	585	491	433
\$/kWh ⁽³⁾	67	52	43	38	30	25	28	23	20	26	22	19

(1) Weekly cycle: Discharge Power = 20 MW; Discharge time = 7 hrs. daily; Charge Power = 20 MW; Charge Time Available = 5 hrs. daily + 24 hrs. Sunday

(2) Based on discharge power level

(3) Based on (t_D)_{max}

(4) Base-line parameter value

Figure 3-38

Projected Cost Reduction for Daily Cycle Redox Battery System

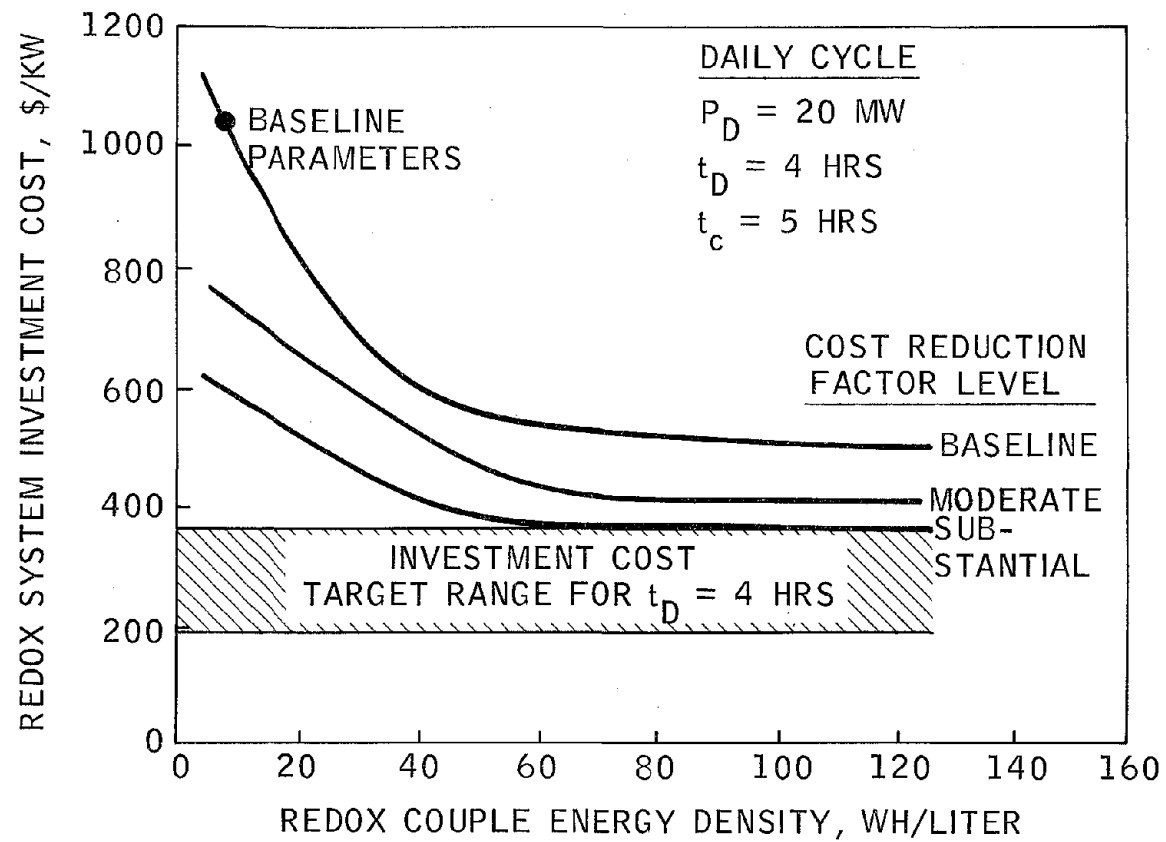
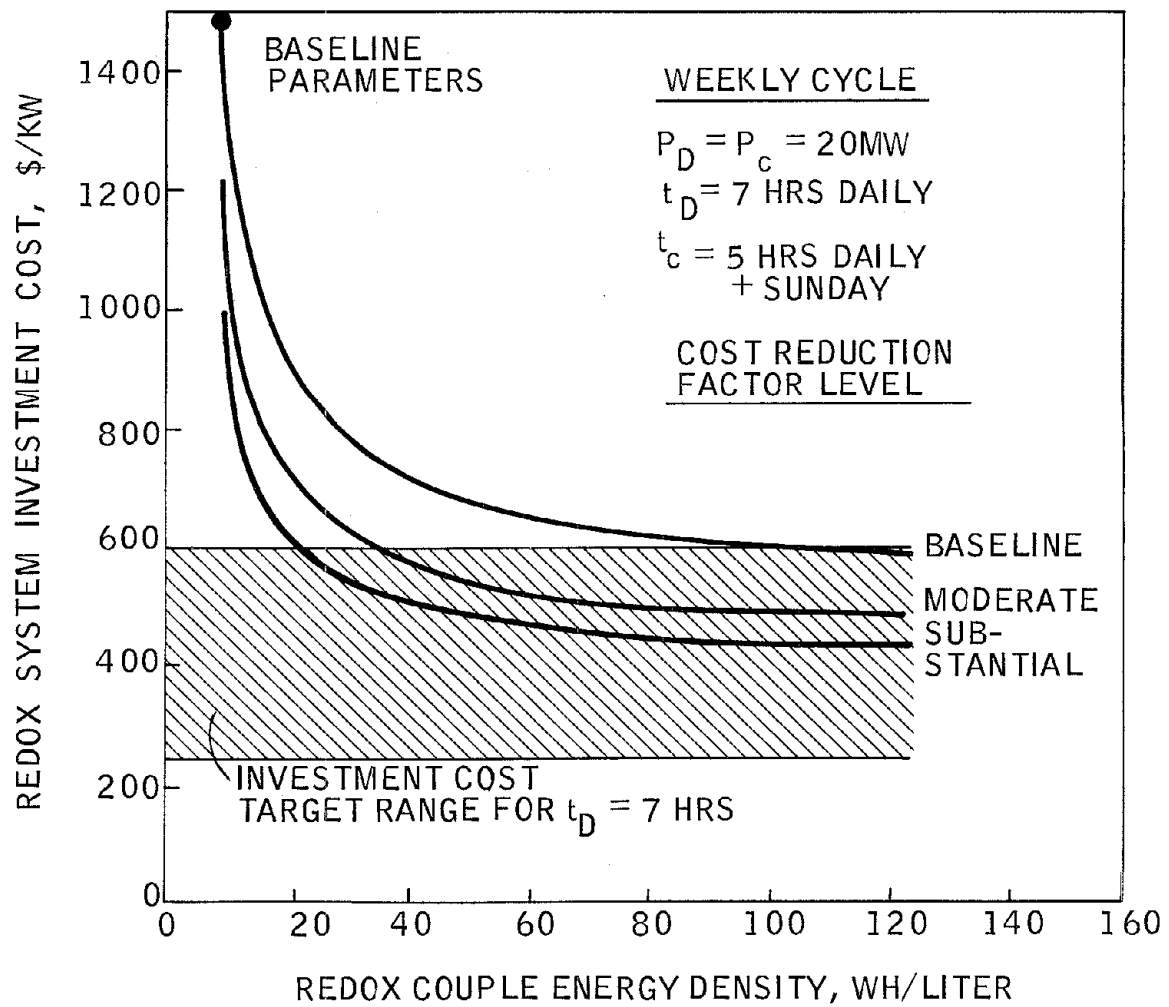


Figure 3-39

Projected Cost Reduction for Weekly Cycle Redox Battery System



4. CONCLUSIONS AND RECOMMENDATIONS

Studies carried out in this program have defined the opportunities and requirements for energy storage devices in electric utilities, including an assessment of candidate electrochemical systems. Major emphasis was placed on defining the techno-economic characteristics of the Redox battery, a promising concept for large-scale energy storage applications.

A review of U.S. electric utility operations, involving the demand for on-peak power delivery and availability of off-peak power for storage, established broad composite requirement categories. Basically, these were peaking and intermediate load demands, distinguished by the average daily demand time period. Roughly, peaking demands occur over a daily range of 1 to 9 hrs, whereas intermediate load demands occur over a longer, 9 to 14 hr daily period. A further characterization defined daily and weekly operating cycles for potential storage systems. Weekly cycles appear particularly attractive, because about 45 percent of the total off-peak energy for storage is available on the week-end. The energy available during the weekend should form an active part of the storage inventory and not be used merely as a convenient source of energy for topping or charge-balancing battery systems.

Brief analysis of new solar and wind-based energy sources established a clear need for auxiliary energy storage capability, but little useful information was uncovered to define specific duty requirements for these applications.

The electrical interface requirements for electrochemical energy storage devices also were studied. Storage systems can be placed at several points in the electric utility transmission and distribution grid. Substation locations are likely initial locations, operating at the 13 kv voltage level with discharge power levels of 10-100 Mw. An average power level of 20 Mw is a convenient size for modelling and analysis purposes. Other interface requirements were established, assuming that storage devices would have to operate with minimal disturbance to existing distribution system operation. Plans to integrate large-scale dc battery systems into utility networks are a relatively recent development, requiring further study for specific battery systems and power conditioning equipment.

Lastly, economic requirements for electrochemical storage devices were established. Cost factors are likely to be the major determinant deciding the future role of these devices. The economic analysis was carried out by defining the break-even capital cost of near-term and long-range battery systems in competition with direct power generation alternatives, including gas turbines for peaking demands and combined cycles for intermediate demands. Rather stringent investment cost targets were defined. Investments in the 20-30 \$/KWH range may be required for high probability of acceptance and market penetration.

These studies showed that battery installation life is critical. Lifetimes approaching 20 yrs appear necessary for effective competition with direct generation. Long life is required to minimize investment amortization charges. Turn-around energy storage efficiency levels of 65-80 percent appear adequate for battery systems.

The assessment of available electrochemical storage systems showed that only the lead-acid battery can be considered for near-term (to 1980) application. However, this system was judged to be too costly and short-lived for wide-spread use. Likely advanced battery system candidates were defined, including: sodium-sulfur, lithium-iron sulfide, sodium-antimony trichloride and zinc-chlorine hydrate.

Here, it was found that costs for complete advanced battery systems were ill-defined. Insufficient experience exists at the multicell level to define operating and maintenance requirements, such as charge-balancing to ensure long-life and good performance. The cost-effectiveness of solutions to materials selection and fabrication problems remains unanswered, although no technological restraints were found that would prevent attainment of required goals in this area after extensive R and D. Available advanced battery cost projections range near the lower limits of the break-even investment targets, but more detailed studies may reveal additional investment requirements for reliable, large-scale systems. Clearly, on-going advanced battery program developments should be monitored to assess the prospects for attaining economic goals.

Two other areas require continued study. First, utility generation expansion analysis should be carried out to assess the impact of wide-spread availability and use of weekly energy storage systems on future generating equipment mix and the resulting cost of delivered energy. These studies would further clarify the attractive opportunities for weekly cycle electrochemical storage systems in electric utilities.

Second, and more urgent, there is a need to monitor long-range trends in utility operation, particularly the availability and cost of off-peak power. The utility industry analyses carried out in this study were based on operating data obtained prior to the oil embargo and natural gas shortage. Although these incidents tend to escalate fossil fuel prices and make direct peaking and intermediate power generation devices less attractive, the resulting higher energy costs may affect utility load demand profiles. Trends in load management and off-peak pricing to smooth load profiles should be studied, because they will affect the need for peak power production and the amount of off-peak power available for charging energy storage devices. Similarly, the impact of delayed nuclear construction on the availability and cost of off-peak power must be reviewed. In effect, reductions in the amount of off-peak power and/or increases in the cost of this power will tend to limit the opportunities for electrochemical (or other) storage devices. Lower break-even investment cost targets would be imposed to compensate for these factors, and battery cost projections may already be too optimistic. Prospective competition from high efficiency fuel cells and from down-rated coal-fired power plants should also be factored into future analyses.

A broad-based study was made to analyze the Redox battery concept. The chief feature of the Redox concept is the decoupling of energy storage and power generation functions using circulating, dissolved reactants. In turn, this permits considerable flexibility in designing systems to cover the full range of potential energy storage applications.

The analysis was carried out using relatively simple models of the Redox system, the Stage 1 Model for daily cycles and the Stage 1.5 Model for weekly cycles. The limitations of these models were defined, including the use of time-averaged performance parameters, rather than concentration-dependent performance. Performance-concentration interactions are a characteristic of Redox battery operations. In turn, reactant concentrations will change with time, so that performance will also be time-dependent. However, the simple models appear adequate for scoping

feasibility studies, aimed at uncovering important parameter interactions and investment cost centers.

A more sophisticated Stage 2 Model of the Redox system also was developed. This model features full load-following capability with Redox cell performance variations as a function of time-varying reactant concentration. In turn, interactions between electrochemical reaction kinetics, mass-transfer and hydrodynamic conditions are included. A more comprehensive Redox cell design analysis is permitted, but here, too, the model contains only one of several alternative approaches to cell configuration. Only limited testing was carried out during program debugging, so the full capability of the Stage 2 Model remains unexplored.

A systems analysis of the Redox battery concept showed that it is economically feasible, if certain performance parameter values can be attained, and if an auxiliary component cost-reduction program can be carried out successfully. Use of relatively conservative base-line parameter values in the Stage 1 and 1.5 Models resulted in high predicted storage system investment costs, well above the break-even cost targets described earlier. Optimistic parameter values were also defined and gave very attractive systems costs. This analysis showed that there is considerable latitude in projecting parameter values that will produce cost-effective designs, although complete attainment of all optimistic parameter levels is unlikely.

The decoupled Redox system is particularly suitable for use in weekly energy storage cycles. Current component cost estimates suggest that the power-related costs of the Redox system are high and the energy storage-related costs are relatively low. Therefore, weekly cycle applications with long discharge time capability are favored.

Other Redox system conclusions reached included:

- The modular nature of the Redox battery trailer configuration and system auxiliaries result in little economy-of-scale beyond 10 MW system size.
- The apparent energy density, WH/liter, of the Redox couple, is a key parameter that correlates well with total system cost. Energy densities above 50 WH/liter will probably be required for cost-effective Redox systems.
- Excessive costs were predicted for the cartridge filter configurations used in the Redox system plot plan. Alternative approaches are required. In fact, cost-reduction opportunities exist for all Redox battery sub-systems.
- Use of volatile, corrosive supporting electrolytes, such as hydrochloric acid, may pose some environmental hazards.

- No attempt was made to develop operating and maintenance costs for the Redox battery. Specific O and M requirements depend on the final choice of Redox couple chemistry and the possible need for periodic reactant and electrolyte regeneration to remove by-products formed after long operating times.

The Redox storage system concept is at an appropriate early point in its development, capable of substantial reduction in projected cost, if incisive process analysis is carried out. These studies would be more meaningful if they were focussed on a specific Redox couple with known physical and electrochemical properties. A plan of action is suggested to develop lower cost Redox systems. This plan includes:

- A search for Redox couples yielding an apparent energy density of at least 50 WH/liter, preferably 100 WH/liter. In addition to high reversible voltage and multi-electron reactants, highly soluble couples are desirable. Polarization effects, reversibility, faradaic efficiency and stability should be defined experimentally. Real reactant costs should be established.

The Redox system should be looked at primarily as a decoupled system. Thus, a broad view should be taken in defining what constitutes an acceptable couple. A search for suitable non-corrosive supporting electrolytes would also be helpful.

- The Redox models assumed perfect ion-selective membrane behavior. Assumed parameter values were used for membrane thickness, resistivity and cost, but the general question of membrane life and ion or water transference was not covered. Efforts to develop suitable selective membranes should continue, including measurements of these transference properties in operating cell configurations.
- Cost reduction analysis, to be carried out for each Redox subsystem. A brief outline follows:
 - + Tankage - Explore use of flexible bladders with or without sprayed concrete coating.
 - + Filters - Develop alternative filtration approaches, including use of in-line porous filters or strainers mounted within the Redox trailer assembly. External sand-bed filters should also be considered. Final resolution of this problem will require a complete reactant loop pressure balance analysis coupled with analysis of specific Redox cell designs. Again, this study should be made for a specific storage application design.

- + Redox Cells - Define specific geometry and materials of construction for the cell frames, conductive structures and electrode deposits.
- + Pumps - In conjunction with the overall system pressure balance, define the minimum acceptable pump discharge design pressure and throughput capacity.
- + Piping - Consider the use of all-plastic piping or flexible hosing.
- + Heat Exchangers - Carry out trade-off studies to define the effect of Redox cell operating parameters on cooling duty with specific Redox couple performance.
- + Power Conditioning - Explore opportunities for projected cost reduction in inverter/rectifier equipment.

In the area of further model studies, continued study and expansion of the Stage 2 Model should be considered. Preliminary testing of the Stage 2 Model, carried out during the debugging process, showed that parasitic power losses due to shuntage currents were high for cell designs with relatively short ports. Future work should stress cell designs and/or operating schemes to minimize shuntage effects. Also, permissible reactant utilization appears to decrease when concentration effects are included in the Redox kinetic predictions. This effect was expected, but additional study, using the Stage 2 Model, is required. A comparison of Stage 2 Model results with those of simpler models should be made to verify the systems conclusions described earlier.

The following features should be added to the Stage 2 Model:

- Incorporation of the flow distribution and pressure drop analysis to permit trade-offs to be made on the effect of increased reactant flow rate on mass transport within the Redox cell. To be meaningful, the total system pressure balance should be considered, but this is difficult to do in a general computer model. The study should focus on a specific energy storage application, say a well-defined weekly cycle, rated at 20 MW maximum discharge power output.
- Modification of the material balance relations within the Redox cell to account for expected non-ideal behavior of the separating membrane. Ion and water diffusion parameters should be added and model predictions of electrolyte management should be checked against experimental data on real cells.

In summary, the studies made in this program show that the Redox battery is an attractive concept that could fill an identified need for utility energy storage systems. However, additional R and D studies are required to verify that specific electrochemical performance goals can be achieved experimentally. A number of pathways exist for reducing the cost of the Redox energy storage systems. These pathways also must be explored, to ensure that the Redox system will be competitive with other advanced battery systems and alternative power generation approaches for meeting utility peaking and intermediate load demands. In a sense, Redox battery development is in its infancy, lacking definition of the "best" real couples for further study. These couples simply must be selected before the Redox concept can be exploited.

5. APPENDICES

<u>Appendix No.</u>	<u>Title</u>
5-1	The Potential for Application of Energy Storage Capacity on Electric Utility Systems in the United States - Part I
5-2	Ibid, Part II
5-3	Electrical Interface Requirements
5-4	Selected Bibliography of Electrochemical Design References
5-5	Flow Distribution and Pressure Drop in Redox Cell Stacks

APPENDIX 5-1

THE POTENTIAL FOR APPLICATION OF ENERGY STORAGE CAPACITY
ON ELECTRIC UTILITY SYSTEMS IN THE UNITED STATES-PART 1

V. T. Sulzberger J. Zemkoski

Public Service Electric and Gas Company
Newark, New Jersey

ABSTRACT

This paper briefly describes the results of the first phase of the systems analysis part of a research project to assess energy storage systems suitable for use by electric utilities. U.S. electric utility systems load and generation data that were collected and analyzed in order to select a number of systems most representative of the electric utility industry are described. The representative systems in turn are used to determine the potential total amount and distribution of off-peak energy available on individual systems on an annual, seasonal, weekly and daily basis. The amount of off-peak energy is described as functions of annual hourly load shape, capacity level assumed available for producing off-peak energy, generator performance characteristics (forced and maintenance outages), and energy storage device round trip efficiency.

INTRODUCTION

The utilization of off-peak energy by electric utilities for charging energy storage capacity for use during the peak load time of day has received increased attention recently because of the energy crisis. The energy crisis emphasized the need to make more effective use of available installed capacity as well as the need to search for new forms of more environmentally acceptable forms of electric generation intermediate and peaking capacity. However, the multitude of unknowns associated with the availability of off-peak energy, the required operating parameters of energy storage devices for electric utility application, and the emerging energy storage technologies established the need for a technology assessment and system analysis in order to identify potential markets, system requirements, and guidelines for R&D priorities. This paper describes the results of the first phase of the system analysis part of such a project entitled "An Assessment of Energy Storage Systems Suitable For Use By Electric Utilities".

Transactions paper published in IEEE publication, "Energy Development II," 76 CH 1102-3-PWR, 1976, pp. 15-23. Will also be published in Transactions on Power Apparatus and Systems.

The extent to which energy storage capacity can be utilized on an electric utility system depends among other factors on the utility's system load characteristics, the system generation mix, the energy storage device characteristics, and particularly, the economics of energy storage capacity compared to other alternative types of peaking and intermediate generating capacity. Based on these factors the system analysis part of this project proceeded with the collection and analysis of U.S. electric utility industry system load and generation data. From this data representative electric utility systems were selected for more detailed analysis in order to determine the amount and distribution of off-peak energy available on an annual, seasonal, weekly and daily basis as a function of load shape and assumed generation capacity levels. In addition, practical limits to the amount of off-peak energy were also identified as a function of energy storage conversion efficiency.

In the second phase of the system analysis to be published at a later date, typical energy storage operating parameters such as operating hours, duty cycles and storage requirements will be identified for serving both the peaking and intermediate-duty system applications. An estimate of the amount of energy storage power capacity that could be supported by a typical electric system will be made. In addition the relative economic competitiveness of energy storage capacity will be examined and breakeven costs for which energy storage could be competitive with other more conventional methods of peaking and intermediate generation will be determined.

ELECTRIC UTILITY SYSTEM DATA

Data-Base Description

The year 1971 was selected as the base data year for the project because it was the most current year for which consistent load and generation data as well as annual hourly system load data for U.S. electric utility systems were available. The sample utility data-base consists of load and capacity characteristics of 199 privately and publicly owned electric systems collected from various sources. 1-II

For the most part the data-base consists of privately owned systems having annual electric operating revenues of \$2.5 million or more and publicly owned systems with operating revenues of \$50 million or more. Several large cooperative systems were also included in the data base so as to be more representative of the U.S. electric utility industry. To be exact, of the 199 systems,

163 are privately owned, 26 are municipals, 5 are federal power agencies and 5 are cooperatives.

Although this data-base of 199 systems represents less than 10% of the utilities in the U.S., it represents about 90% of the total installed capacity of 367,000 megawatts and 97% of the 1.6 billion megawatt-hours of net energy generated in the U.S. in 1971.

The load data collected consists of annual system load factors, system peak loads, peak season, and total net annual energy produced for load. The generation data includes the system installed capacity and its percentage generation mix according to the four general categories: fossil or steam, hydro and pumped storage, gas turbines and diesels, and nuclear. Also included is data on utility annual electric operating revenues, type of ownership (private or public), and National Electric Reliability Council (NERC) membership.

Consistent with the 1971 data-base, the Edison Electric Institute made available on a confidential basis the 1971 annual hourly load data for about 150 individual utilities and/or pools which had been collected as part of an EEI load diversity study.¹² This data was made available because of the possible benefit of the energy storage assessment study to the electric utility industry in general.

Average System Size

A statistical analysis¹³ of the 1971 utility data base was made to determine the average utility system size in terms of peak load and annual energy produced for load. Table I shows the results of that analysis. Of the 199 systems, 65% were summer peaking systems which supply 70% of the total energy generated in the U.S.

TABLE I
AVERAGE ELECTRIC UTILITY SYSTEM
SIZE - 1971 DATA BASE

	All Systems	Summer Peaking Systems	Winter Peaking Systems
Number of Systems	199	129	70
System Peak Load (MW)			
Average	1,500	1,700	1,100
Minimum	6	17	6
Maximum	16,700	11,000	16,700
System Annual Energy (MWh x 10 ³)			
Average	7,900	8,700	6,400
Minimum	27	85	27
Maximum	93,500	54,000	93,500

The average size system in terms of peak load was found to be about 1500 megawatts. The average summer peaking system is about 600 megawatts larger than the average winter peaking system. However, the system with the largest peak in the sample is a winter peaking system. The systems with the smallest peak loads in the sample are a summer peaking system with a 17 MW load, and a winter peaking system with a 6 MW load.

The average size system in terms of system annual energy produced for load considering all 199 systems is about 7900 x 10³ MWh. The annual energy of the average summer peaking system is about 2300 x 10³ MWh greater than the winter peaking system. However, once again the system with the largest amount of annual energy is a winter peaking system. A winter system also had the smallest amount of annual energy with 27,000 MWh.

Load Factor Analysis

The annual system load factors of the 199 systems in the 1971 data base were analyzed to determine the range of annual load factors representative of U.S. electric utility systems. Table II summarizes the results of this analysis. The annual load factors are expressed in percent and are defined as the percentage ratio of net annual energy for load to the product of annual peak load (one hour integrated peak demand) and annual hours.

TABLE II
ELECTRIC UTILITY 1971 ANNUAL
SYSTEM LOAD FACTOR ANALYSIS

Description (%)	All Systems	Summer Peaking Systems	Winter Peaking Systems
Range	45	40	31
Minimum Value	37	37	31
Maximum Value	82	77	82
Average			
Unweighted	59	57	62
Weighted (Peak Load)	60	59	65
Weighted (Annual Energy)	61	59	65

The annual load factors were found to range about 45 percentage points from a low of about 37% to a high of about 82%. The range of the annual load factors for the summer peaking companies was 9 percentage points more than the winter peaking companies. In general the annual load factors for the winter peaking companies are higher than the summer peaking companies.

Since the system peak loads and annual system energy of the data-base were found to vary over a wide range, the average annual load factors were calculated on both an unweighted and weighted (peak load or annual energy) basis. On a weighted (peak load or energy) basis, the average system load factors were found to be only a few percentage points higher than on an unweighted basis. For summer peaking companies, on a weighted basis, the average annual load factor is 59%. On a similar basis, the average annual load factor for winter peaking companies is 65%.

During the course of this study more recent load factor data appeared in the literature for the year 1974.¹⁴ This data was analyzed in the same manner and the average unweighted and weighted annual system load factors for 1974 were essentially identical to the 1971 results.

The 1971 load factor analysis also showed that the sample data of annual load factors very closely represented a normal distribution. The frequency distribution of the annual load factors for the 1971 utility data base is shown in Figure 1. Also shown on this figure are separate distributions for the winter and summer peaking systems. The peak load weighted average annual load factors for all systems, summer peaking systems and winter peaking systems are also identified.

Figure 2 shows the cumulative frequency annual load factor distribution. Approximately 140 or 70% of the 199 systems were found to have annual load factors between 50 and 65%, 20% had load factors below 50% and only 10% had load factors above 65%.

Generation Characteristics

The generation capacity mix of each of the utilities in the 1971 data base was categorized into four general types as follows: conventional steam units, hydro and/or pumped storage, gas turbines and/or diesels, and nuclear units. Only 18 of the 199 utilities reported nuclear capacity on their system, half of the utilities reported having hydro and/or pumped storage units, 85 percent of the utilities reported having some conventional steam capacity, and about 2/3 of utilities included gas turbines and/or diesels in their capacity mix. The analysis showed that the average generation capacity mix of electric utilities in 1971 on a percentage basis consisted of conventional steam, 80%; hydro and/or pumped storage, 11%; gas turbines and/or diesels, 7%; and nuclear, 2%.

REPRESENTATIVE SYSTEMS

Based on a statistical analysis of utility system annual load factors, availability of annual hourly load shapes, system size, generation mix, regional or geographic representation of the U.S., and a valley to peak load ratio analysis, a total of eight typical systems were selected from the 1971 electric utility data-base as representative of the range of U.S. electric utility systems. Because of possible differences in load characteristics of summer and winter peaking systems, three summer peaking systems and three winter peaking systems representative of average, high and low annual load factor systems were selected. In addition, in order to provide some insight into the effect of power pooling on the amount and distribution of off-peak energy, a major power pool and a member company of that pool were included as representative systems.

The eight representative systems selected are shown in Table III. Systems A, B and C are summer peaking with annual load factors of 48%, 60% and 68%, respectively. These systems are representative of the southern regions of the U.S. with system peak loads in the range of 2000- 7000 megawatts.

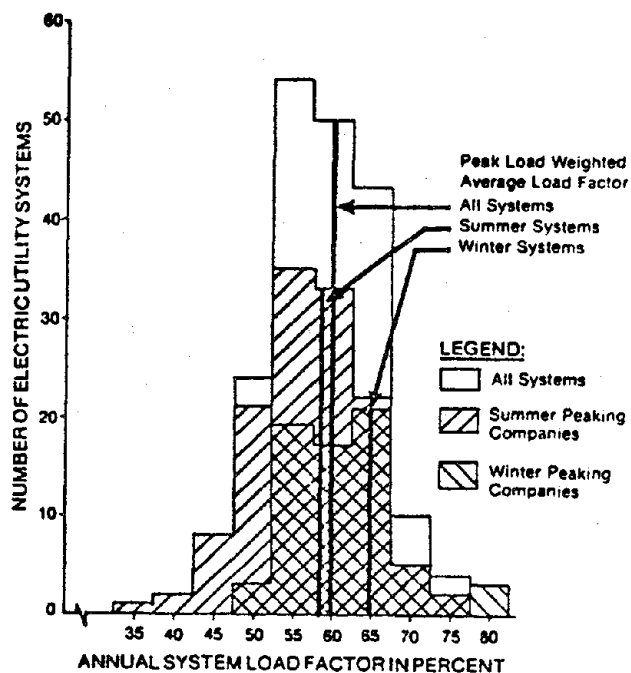


Fig. 1 Frequency Distribution of Electric Utility 1971 Annual System Load Factors

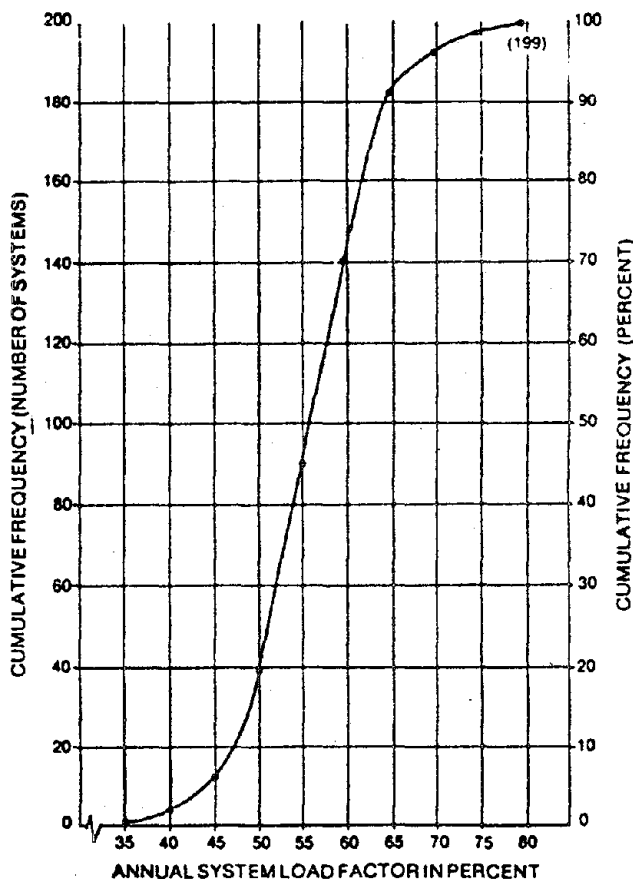


Fig. 2 Cumulative Frequency Distribution of Electric Utility 1971 Annual System Load Factors

TABLE III
REPRESENTATIVE ELECTRIC SYSTEM

Peak Season	System	Annual Load Factor(%)
Summer	A	48
	B	60
	C	68
Winter	A'	55
	B'	63
	C'	78
Summer	Y	54
	Z	61

The selected representative winter peaking systems identified in Table III as systems A', B' and C' have annual load factors of 55%, 63% and 78%, respectively. These winter peaking systems are representative of the northern region of the U.S. encompassing a range of systems with annual peak loads of about 600 to 2000 megawatts.

Table III shows that both the power pool, system Z and the member company, system Y are summer peaking systems. The power pool has an annual load factor of 61% and the member company has an annual load factor of about 54%.

Note that systems B and B' are more representative of the average U.S. summer and winter peaking utilities, respectively. The average annual load factors of these systems are similar to the average annual load factors of Table II for summer peaking and winter peaking systems.

Generation Mix

The average percentage mix of the generating capacity of systems A, B, C, A', B' and C' was found to be as follows: Conventional steam, 83%; hydro and/or pumped storage, 14%; and gas turbines and/or diesels, 3%. None of the selected representative systems had any nuclear units in service in 1971. This average percentage generation mix for the six representative systems very closely approximates the average generation mix of the 1971 utility data base.

The generation mix of the power pool is as follows: conventional steam, 75%; hydro and/or pumped storage, 3%; gas turbines and/or diesels, 20%; and nuclear, 2%. The member system generation mix is as follows: 73%, 2%, 25% with no nuclear, respectively.

Weekly Peaks

Table IV shows for all representative systems a tabulation by season of the average weekly peak loads in percent of the annual peak load. This analysis indicated that the differences in weekday peaks between the peak season and the other three non-peaking seasons is the main reason why electric systems have poor system annual load factors. Table IV also shows that representative utility system Y very closely follows the weekly peaking pattern of power pool Z.

TABLE IV
SEASONAL AVERAGE WEEKLY
PEAK LOADS AS A PERCENT
OF ANNUAL PEAK LOAD

System	Season			
	Winter	Spring	Summer	Fall
A (48) ^a	53	51	83	56
B (60)	78	72	85	78
C (68)	86	81	89	86
A' (55)	84	65	54	72
B' (63)	88	75	78	84
C' (78)	89	87	88	90
Y (54)	68	66	80	68
Z (61)	76	71	84	74

a) Annual System Load Factor

Period Load-Factors

Table V shows the average seasonal, weekly and daily period load-factors for the representative systems. Note in general that for all systems the period load-factor progressively increases going from the annual period down to the daily period.

TABLE V
AVERAGE PERIOD LOAD FACTORS(%) WITH DEVIATIONS

System	Annual	Seasonal	Weekly	Daily
A	48	59±9.9	75±4.4	83±3.
B	60	66±5.1	75±2.2	80±2.9
C	68	70±2.0	76±2.9	86±1.0
A'	55	65±3.6	75±2.9	81±1.5
B'	63	69±1.7	76±1.4	82±0.5
C'	78	80±1.7	84±3.2	89±1.3
Y	54	61±7.1	74±4.3	83±1.7
Z	61	67±5.0	76±3.4	83±1.5

$$\text{Period \% Load Factor} = \frac{\text{Period Energy (MWh)} \times 100}{\text{Maximum Period Peak (MW)} \times \text{Period Hrs}}$$

The actual seasonal load factors were found to vary more for the systems with lower annual load factors than for the systems with higher annual load factors. For example, the seasonal load factors of system A varied from 50 to 69 percent while the seasonal load factors of system C' vary only from 78 to 82 percent. However, to a large extent this was due to the assumption made to divide the year into 13 week seasons. If a division more representative of the load level had been selected less variation in the seasonal load factors may have been observed.

The weekly load-factor of all systems was found to be more stable than the seasonal load-factors averaging about 75% for all systems except C'. The average daily load factor was calculated to be about 83% with very little deviation whatsoever.

Load Shape Ratios

A valley to peak load ratio analysis was performed to determine if the selected representative systems were typical of the U.S. electric utility industry as far as load curves or shapes are concerned. From the annual hourly load data of approximately 100 utility systems for which such data was available, average annual weekday, Saturday and Sunday daily load curves were used to determine valley to peak load ratios for average Saturday, Sunday and weekdays. The results of this electric utility analysis are shown in Table VI.

TABLE VI
U.S. ELECTRIC UTILITY
LOAD SHAPE RATIOS (%)
WITH DEVIATIONS

Description	Load Ratio
Average Weekday Valley Load/Peak Load	59 \pm 7
Average Saturday Valley Load/Peak Load	66 \pm 8
Average Sunday Valley Load/Peak Load	66 \pm 7
Average Saturday Peak/ Weekday Peak	88 \pm 6
Average Sunday Peak/ Weekday Peak	82 \pm 6

Table VI indicates that the variation in daily load shape is greater on a weekday than on an average Saturday or Sunday since the weekday valley load to weekday peak load ratio is less than that of Saturday or Sunday. A comparison of the last two ratios of Table VI also shows that Saturday peak loads are generally higher than Sunday peaks. Except for system C, the representative systems valley to peak load ratios for the annual average weekday, Saturday, and Sunday were found to be within one standard deviation of the electric utility averages.

OFF-PEAK ENERGY

Analysis Technique

The amount and distribution of off-peak energy on each of the representative systems was determined by computer analysis of the 1971 hourly load data. For the analysis the calendar year was divided into four seasons each consisting of thirteen weeks. The Spring, Summer and Fall seasons consisted of thirteen consecutive weeks while the Winter season was divided into two parts composed of the last 3 weeks of December and the first 10 weeks of the year.

For each system, a number of assumed base-load capacity levels were specified and the amount of off-peak energy associated with each level was determined. The specified capacity level was adjusted on a seasonal basis for both maintenance and forced outages

in order to provide a more realistic indication of the amount of off-peak energy available. Published industry average forced and maintenance outage rates of 10 percent and 5 weeks per year respectively were applied to the base capacity. No base capacity maintenance outages were scheduled during the peak load seasons and the allocation of maintenance to the three other seasons was performed on the basis of levelizing both the base load maintenance outages as well as the overall system reserve capacity over the year.

Figure 3 pictorially shows how the off-peak energy was calculated for a given assumed capacity level. Representative system B average seasonal weekday and weekend load shapes are used here to represent the annual hourly 8760 system B loads actually used in the computer analysis. The assumed capacity level of 70% (of peak load) was adjusted for forced and maintenance outages as previously described.

The average seasonal capacity available to supply system base load requirements and charge off-peak energy storage devices after outage adjustments is shown to be about 55% (of peak load) in the spring, fall and winter seasons and about 63% in the summer. As system B is a summer peaking system, no maintenance was permitted on the base capacity in the summer season. Therefore, the average available base capacity for the summer season was adjusted only for forced outages.

The off-peak energy calculated on a daily basis in the computer program is shown by the shaded area below the adjusted capacity level and above the load requirements. Also shown on the diagram are the seasonal peak load and the seasonal minimum load for system B to demonstrate the extent of the variation in the system B load curve.

Total Amount

Figure 4 shows the generalized relationship observed between the total annual amount of off-peak energy available on an electric system, the system annual load factor and any assumed base-load capacity levels represented as a percent of system peak load. This figure was developed by plotting the total amount of off-peak energy associated with the various assumed base-load capacity levels for each of the representative systems. Smooth curves were then drawn through the points associated with a particular capacity level.

Although developed for the representative systems, these curves could be used to estimate the total annual amount of energy available on any electric utility. For example, for representative system B which is a summer peaking system with a 60% annual load factor, at an assumed base-load capacity level of 70% of peak load, the amount of off-peak energy available on an annual basis amounted to 8% of the total energy produced for load by system B.

ORIGINAL PAGE IS
OF POOR QUALITY

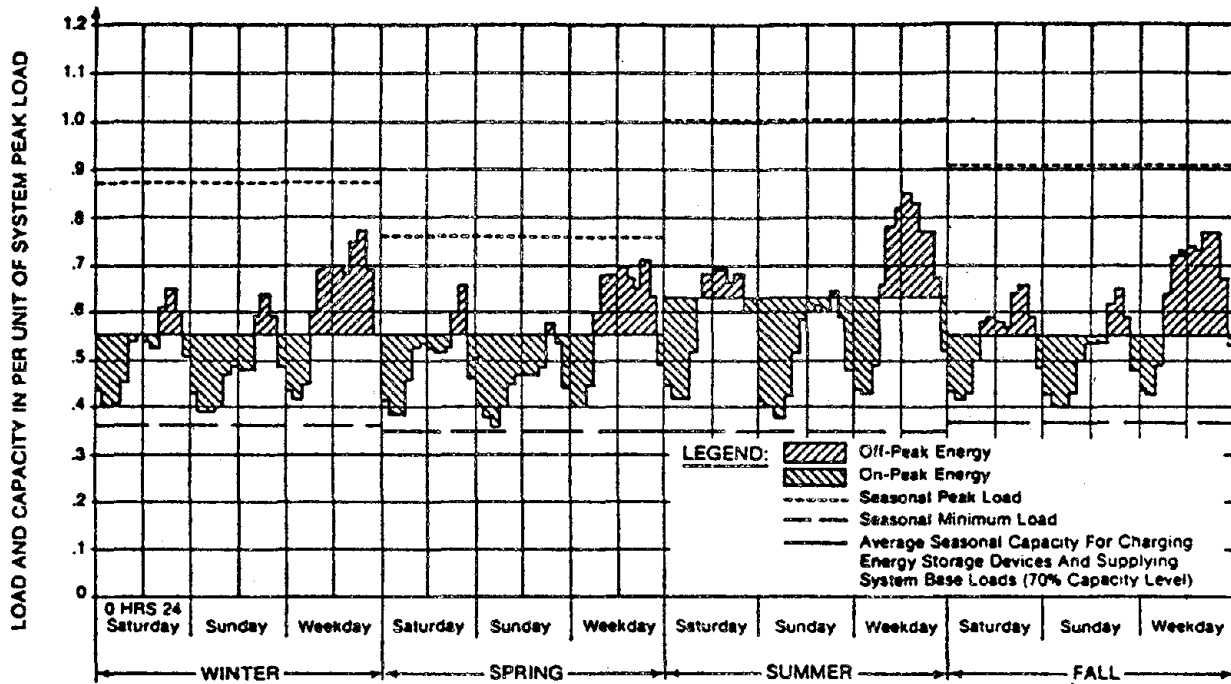


Fig. 3 Seasonal Distribution of Off-Peak Energy on Representative System B for the 70% Capacity Level

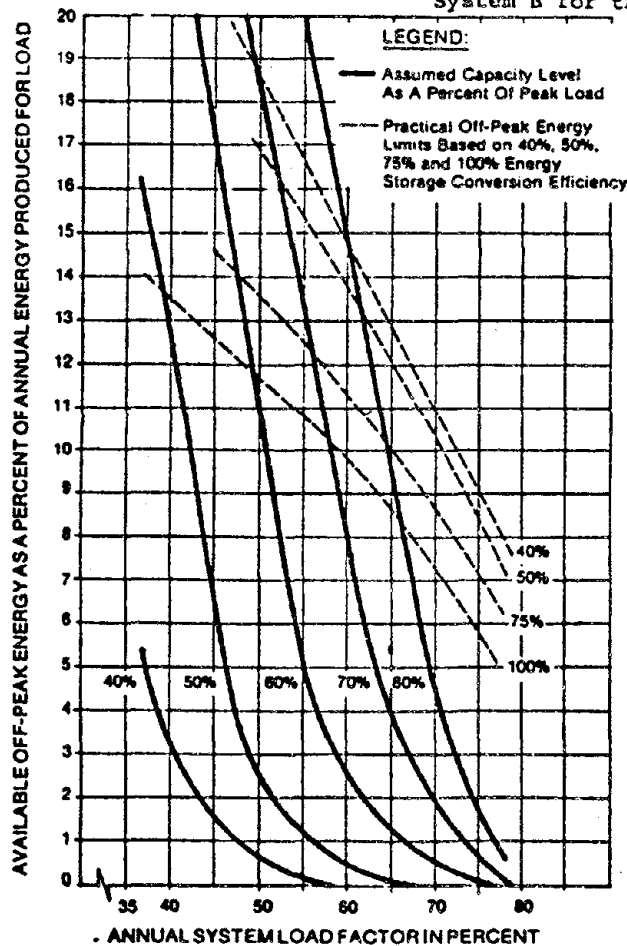


Fig. 4 Total Annual Off-Peak Energy Limits For Electric Utility Systems

In general, Figure 4 shows that the off-peak energy availability begins to become significant as the assumed capacity level approaches the load factor of the system. It also shows that for the systems with the lower annual load factors, more off-peak energy as a percent of total system energy becomes available at any given capacity level.*

The total amount of off-peak energy that can be utilized by any electric system is limited by the energy storage conversion efficiency. For example, for a 100 percent energy storage conversion efficiency, the base-load capacity level for which the off-peak energy is equal to the on-peak energy defines a system limit for the extent to which energy storage capacity could be utilized. Neglecting distribution, this equal energy criterion provides a first approximation to the limit of the annual amount of off-peak energy on the representative systems. If one were to assume a lower conversion efficiency, the amount of on-peak energy capable of being supplied by off-peak energy would be reduced.

The dashed lines shown on Figure 4 represent the upper off-peak energy limits for electric systems assuming energy storage conversion efficiencies of 40, 50, 75 and 100 percent. The off-peak energy located below these curves can be viewed as the practical range of off-peak energy availability which may be considered for use with energy storage capacity.

* These relationships will be discussed further in the next monthly.

This analysis shows that based on an energy storage conversion efficiency of 100%, utilization of all the off-peak energy available on an annual basis could theoretically supply approximately 10% of the annual energy requirements of electric utilities.

Seasonal Distribution

Table VII shows the seasonal distribution of the total or limited annual off-peak energy for each of the representative systems for the assumed base-load capacity levels associated with a 75% energy storage conversion efficiency. All the systems, including the power pool (System Z) appear to have a fairly even distribution of off-peak energy ranging between 16 and 45 percent per season.

TABLE VII
SEASONAL DISTRIBUTION OF OFF-PEAK ENERGY
IN PERCENT OF TOTAL OFF-PEAK ENERGY

System	Assumed Capacity Level (%) ^b	Seasonal Distribution ^a			
		Winter (%)	Spring (%)	Summer (%)	Fall (%)
A (48) ^c	61	26	33	16	25
B (60)	75	21	26	34	19
C (68)	86	19	26	36	19
A' (55)	69	16	22	45	17
B' (63)	79	30	26	25	19
C' (73)	97	45	16	23	16
Y (54)	69	23	27	27	23
Z (61)	77	19	27	32	22

- a) 13 weeks in each season.
b) Percent of system peak load.
c) System Annual Load Factor.

Note in particular the very even seasonal distribution of off-peak energy for systems B and B', the systems which are most representative of the majority of electric utilities which have load-factors in the range of 55-65% and representing about 80% of the total energy produced in the U. S. A.

Weekly Distribution

Table VIII shows for each system for each season the average amount of off-peak energy available on a weekly basis for capacity levels associated with a 75% energy storage conversion efficiency. The amount of off-peak energy available each week in percent of total off-peak energy was found to vary over a range from about 1% to 3% with the average at about 2% for all systems including the power pool (system Z).

TABLE VIII
SEASONAL AVERAGE WEEKLY OFF-PEAK ENERGY
IN PERCENT OF TOTAL OFF-PEAK ENERGY

Representative System	Assumed Capacity Level (%) ^b	Average Weekly Energy ^a			
		Winter (%)	Spring (%)	Summer (%)	Fall (%)
A (48)	61	2.0	2.5	1.3	1.9
B (60)	75	1.7	2.0	2.7	1.4
C (68)	86	1.4	2.0	2.9	1.4
A' (55)	69	1.2	1.7	3.5	1.3
B' (63)	77	2.3	2.0	2.0	1.4
C' (73)	97	3.5	1.2	1.8	1.2
Y (54)	69	1.8	2.1	2.1	1.7
Z (61)	77	1.5	2.1	2.5	1.7

- a) 13 weeks in each season.
b) Percent of system peak load.

Daily Distribution

Table IX shows for each system the actual average off-peak energy in percent of total off-peak energy available on a daily basis during each season. The amount of energy available each weekday was found to vary from about .0 to .4 percent of total off-peak energy with the average being about .2%. This table also shows that more off-peak energy is available on Sunday than on Saturday. In addition, an average Saturday and an average Sunday each have more off-peak energy than a typical weekday.

TABLE IX
SEASONAL AVERAGE DAILY OFF-PEAK ENERGY
IN PERCENT OF TOTAL OFF-PEAK ENERGY

System	Capacity Level ^a	Winter (%)			Spring (%)			Summer (%)			Fall (%)		
		Wkdy.	Sat.	Sun.	Wkdy.	Sat.	Sun.	Wkdy.	Sat.	Sun.	Wkdy.	Sat.	Sun.
A (48) ^b	61	.2	.4	.5	.3	.5	.6	.2	.2	.3	.2	.3	.5
B (60)	75	.2	.3	.5	.2	.4	.6	.3	.5	.6	.2	.2	.4
C (68)	86	.1	.3	.7	.1	.3	1.0	.3	.5	1.1	.1	.2	.8
A' (55)	69	.2	.2	.2	.2	.3	.4	.4	.6	.7	.2	.2	.2
B' (63)	79	.2	.5	.6	.2	.4	.6	.2	.3	.5	.1	.3	.4
C' (78)	97	.4	.7	.7	.1	.2	.4	.2	.2	.5	.2	.2	.3
Y (54)	69	.2	.4	.5	.2	.4	.6	.2	.4	.5	.2	.4	.5
Z (61)	77	.1	.3	.4	.2	.4	.6	.3	.4	.6	.2	.3	.5

- a) Percent of System Peak
b) Annual System Load Factor.

ORIGINAL PAGE IS
OF POOR QUALITY

For each system, the actual weekday (five)/weekend (Saturday and Sunday) split of this weekly off-peak energy was found to vary in a range from 60/40 to 50/50 percent. This type of off-peak energy split favors energy storage capacity capable of operating on a weekly cycle - i.e., charging to almost full capability on the weekend and then discharging each weekday with some additional charging during the offpeak periods of each weekday until the storage reduces to zero by the next weekend.

FUTURE PROJECTIONS

Load Factors

The future trend of annual system load factors was determined from an analysis of regional utility data supplied by the nine regional reliability councils in the U.S. Each regional council provided, on a confidential basis, a sampling of the 1984 peak load and energy forecast for the major utility systems in their respective councils. This 1984 data base represents about 45 percent of the forecast 1984 non-coincident U.S. summer peak load or about 52 % of the total energy forecast to be produced in the U.S. in 1984. The data supplied by the regional councils is consistent with the Docket R-362 April 1974 filings made with the FPC.

Although the 1984 annual load factors considering all systems, are projected to have a range similar to the range of the 1971 data-base load factor analysis, the 1984 range of annual load factors for the summer peaking systems was calculated to be about 14 percentage points less than the range of winter peaking systems. This is a reverse of the 1971 load factor analysis where the summer utilities showed an annual load factor range of 9 percentage points more than the winter utilities.

For summer peaking systems, the average 1984 annual load factor on both a weighted (peak load or energy) and unweighted basis is about 4 percentage points lower than the average 1971 annual load factors. For winter peaking companies, the 1984 weighted (peak load or energy) and unweighted load factors are only about 2 percentage points lower than the 1971 annual load factors. However winter peaking systems continue to have higher load factors than summer peaking systems.

The projections indicate decreasing annual load factors in the future, and possible increased interest in the application of energy storage devices as well as other load management techniques for improving system load factors.

Generation Mix

Based on the generation data filed by the nine regional electric reliability councils with the Federal Power Commission as of April 1, 1974, the FPC reported the following approximate mix of generating capacity in the contiguous U.S. for 1993: fossil fueled, 50%; nuclear, 40%; hydroelectric, 10%.¹⁵

Compared to the 1971 data base generation mix, fossil fueled generators are projected to decrease from about 87% of the capacity mix to 50% in 1993 and hydro power will decrease from 11% to about 9%. During the past year since the filing of the April 1974 reports with the FPC, many utilities have reduced their load forecasts and consequently have delayed their generation expansion program. In any event, the amount of nuclear capacity is still expected to increase substantially in the 1990-2000 period compared to the average 2% nuclear capacity represented in the 1971 utility data base. It is this nuclear capacity as well as the base-load fossil fueled capacity which is expected to be available at off-peak periods for charging the energy storage devices.

CONCLUSIONS

An analysis of the load characteristics of electric utilities representing over 95% of the energy generated for the year 1971 showed that regardless of the geographical location of the utility or when the annual system peak load occurs, electric utilities have extremely similar load characteristics at the daily and weekly levels. Daily and weekly load factors showed very small deviations from the respective averages. Similarly average weekday, Saturday and Sunday valley to peak load ratios and average Saturday and Sunday peak to weekday peak load ratios showed the same type of consistency.

A parametric analysis of individual utilities based on specifying capacity levels as a percent of system peak and adjusting these levels for maintenance and forced outages according to common utility practices showed that the distribution of off-peak energy is relatively even over the entire year on a seasonal, weekly and daily basis. In addition a consistent weekday to weekend split of approximately 60/40 to 50/50 percent of the energy was observed.

The analysis further showed that based on an energy storage conversion efficiency of 100%, utilization of all off-peak energy on an annual basis could theoretically supply approximately 10% of the energy requirements of electric utilities.

The results of this analysis provide an incentive for further investigation of the energy storage concept for large scale electric utility application. Subsequent publications will provide a realistic indication of the amount of energy storage capacity capable of being supported by the available off-peak energy; an indication of the duty-cycle requirements of energy storage capacity; and an examination of the economics of energy storage capacity for peaking and intermediate-duty electric utility application.

ACKNOWLEDGEMENTS

The results in this paper were developed in connection with a research project jointly sponsored by the Energy Research and Development Administration and the Electric Power Research Institute. The system analysis work was performed by the Public Service Electric and Gas Company under contract to the above agencies. The authors wish to thank Messrs. R. A. Fisher and J. M. Torres for their assistance in the system analysis and Ms. M. T. Burger for her typing assistance.

REFERENCES

1. Federal Power Commission Report FPC S-228, "Statistics of Privately Owned Electric Utilities in the United States, 1971 Classes A and B Companies," U.S. Government Printing Office, Washington, DC, October 1972.
2. "Uniform Statistical Report - Year Ended December 31, 1971," (Submitted by Companies to the American Gas Association, Edison Electric Institute and Financial Analysts).
3. 1971 Company Annual Reports.
4. Electrical World, "Directory of Electric Utilities, 1972-73," 81st Edition, McGraw-Hill, Inc. New York 1972.
5. Moody's, "Public Utility Manual 1972," Moody's Investors Service, Inc., New York, New York 1972.
6. Federal Power Commission Report FPC S-228, "Statistics of Publicly Owned Electric Utilities in the United States, 1971," U.S. Government Printing Office, Washington, DC, October, 1972.
7. Rural Electrification Administration Bulletin 1-1, "1971 Annual Statistical Report, U.S. Dept. of Agriculture, Rural Electric Borrowers," U.S. Government Printing Office, Washington, DC, October 1972.
8. Public Power Magazine, "January - February 1974 Directory Issue," Volume 32, Number 1 Washington, DC.
9. REA Bulletin 111-2, "33rd Annual Report of Energy Purchased By REA Borrowers," U.S. Dept. of Agriculture, Rural Electrification Adm., Washington, DC 20250, 1971.
10. Power Annual Report 1971 "Tennessee Valley Authority," Tennessee Valley Authority, Knoxville, Tennessee, 1971.
11. Municipal and Cooperative Distributors of TVA Power, "1971 Operations," Knoxville, Tennessee, Sept. 1971.
12. LEI Subcommittee Report, "Ten-Year Report on Load Diversity Based on 1962-71 Load Data," Edison Electric Institute, New York, New York.
13. National Bureau of Standards Handbook 101, "A Computer Program for Statistical and Numerical Analysis," U.S. Department of Commerce, U.S. Government Printing Office, Washington, D.C., 20402, March 1966.
14. LEI Publication No. 74-57, "Report on Equipment Availability for the Ten-Year Period, 1964-1973," Edison Electric Institute, New York, New York, December 1974.
15. Federal Power Commission News Release, "FPC Issues Staff Report on Electric Utility Expansion Plans for 1984-93," released date September 24, 1974, No. 20692.

ORIGINAL PAGE IS
OF POOR QUALITY

THE POTENTIAL FOR APPLICATION OF ENERGY STORAGE CAPACITY
ON ELECTRIC UTILITY SYSTEMS IN THE UNITED STATES - PART II

V. T. Sulzberger J. Zemkoski

Public Service Electric and Gas Company
Newark, N. J.

ABSTRACT

This paper briefly describes the results of the second phase of the systems analysis portion of a research project to assess energy storage systems suitable for use by electric utilities. Estimates of the maximum on-peak energy and power requirements capable of being supported by so-called base-load supplied off-peak energy are provided for the U.S. electric utility industry. A generalized relationship observed among available off-peak energy, on-peak energy requirements, annual system load-factor and assumed base-load capacity levels for charging energy storage systems is described. The distribution of both the on-peak and the off-peak energy is also described on a seasonal, weekly and daily basis. A complete spectrum of duty cycle parameters including charge and discharge times, charge to discharge power ratios, operating time and frequency, and required storage capability are defined for energy storage systems for the peaking and intermediate generation applications on electric utilities based on daily and weekly operating cycles. In addition, the effect of overall energy storage system efficiency on the amount of supportable on-peak energy storage capacity is analyzed.

INTRODUCTION

This is the second paper in a series of papers describing the system analysis phase of a research project to assess energy storage systems suitable for use by electric utilities. In the first paper the collection and statistical analyses of U.S. electric utility systems load and generation data were described.¹ Based on these analyses, a number of utility systems representative of the range of electric utilities in the U.S. were selected for more detailed analyses. For these representative systems, the total amount and distribution of off-peak energy available on an annual, seasonal, weekly and daily basis were determined. In addition a generalized relationship observed among the total annual off-peak energy, the annual system load factor, the energy storage system overall efficiency, and assumed base-load capacity levels for charging energy storage systems was identified and shown to be applicable to the U.S. electric utility industry.

SUBMITTED FOR
PRESENTATION AT THE
1976 IEEE SUMMER POWER
MEETING

This paper continues the series with the inclusion of the analysis for on-peak energy requirements. The maximum amount of on-peak energy capable of being supported by the off-peak energy is identified for U.S. electric utilities. In addition, the distribution of annual on-peak energy requirements on a seasonal, weekly and daily basis are described and compared to the distribution of available off-peak energy.

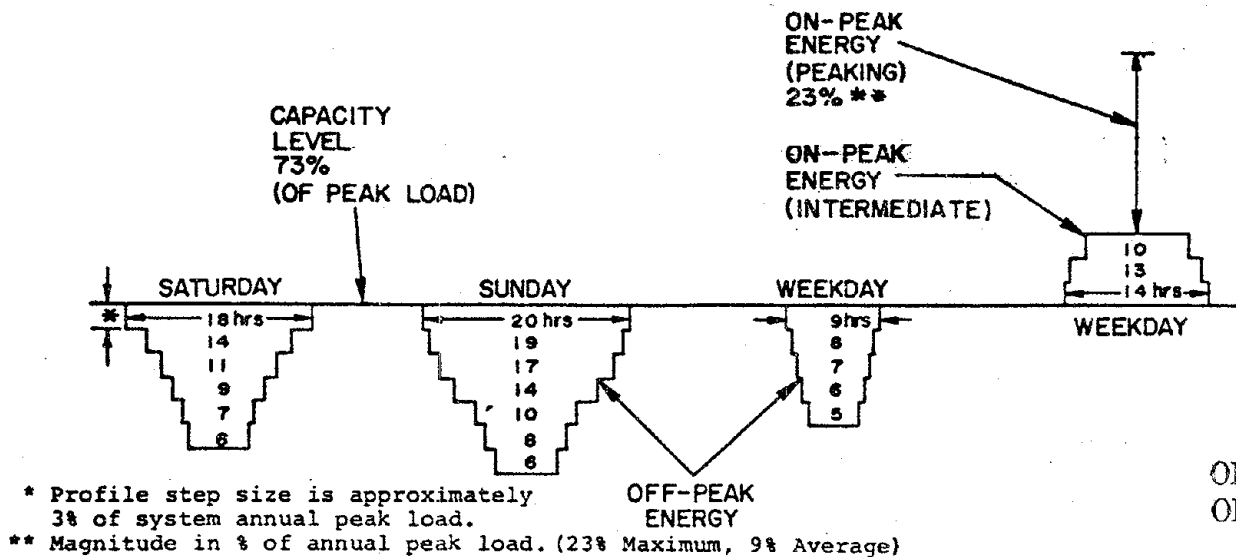
The maximum amount of energy storage power capacity capable of being supported by available off-peak energy is estimated based on an analysis of the characteristics of both the off-peak and on-peak energy of the representative systems. A complete spectrum of duty cycle parameters such as charge and discharge times, charge to discharge power ratios and storage capability in hours are defined for this supportable energy storage capacity.

The last phase of the system analysis, to be published at a later date, will describe some of the energy storage technologies and their associated costs. The relative economic competitiveness of the near to intermediate term energy storage technologies will be examined in terms of breakeven costs for which the energy storage systems would be competitive with other more conventional forms of utility peaking and intermediate generation capacity.

DUTY CYCLE ANALYSIS METHOD

The annual hourly integrated loads of the six electric utilities selected as being representative of the range of electric utility systems in the U.S. were analyzed to determine the range of desirable operating characteristics for energy storage systems. A step-function load and energy profile of the average annual off-peak energy available and the average annual on-peak energy requirements for various assumed base-load capacity levels were developed for each representative system by computer analysis of the actual system annual hourly load data.² Figure 1 illustrates such a step-function for representative system B (summer peaking system, 60% annual load factor).

The off-peak (or on-peak) energy and load profile was developed by measuring in designated step sizes, here taken to be 3% of annual peak load, the average number of consecutive hours the load was less (or more) than the assumed base-load capacity level (after correction for maintenance and forced outages over the year). The profile of Figure 1 represents only that portion of the total available off-peak energy and on-peak energy requirements that would occur on a consistent basis over the 52 weekends and 260 weekdays of the year. The on-peak energy requirements are essentially the intermediate loads on system B which occur every weekday.



ORIGINAL PAGE IS
OF POOR QUALITY

Fig. 1 System B Average Annual Off-Peak and On-Peak Energy and Load Profiles for the 73% (of Peak Load) Capacity Level

Those on-peak energy loads that occur less frequently on a more random basis and also contribute to the on-peak energy requirements are referred to as peaking loads and are shown for system B to range up to 23% of annual peak load in magnitude.

The 73 percent (of peak load) capacity level for system B represents that capacity level for which the annual off-peak energy would be able to supply all of the on-peak intermediate and peaking load energy requirements. An energy storage system capable of satisfying these system conditions would have to be 100 percent efficient. For system B, the maximum amount of on-peak energy that could be supplied by the off-peak energy amounts to approximately 10% of system's B total annual energy requirement. Similar capacity levels and maximum percentages were developed for the other representative systems and the results plotted in Figure 2.

The total amounts of off-peak and on-peak energy associated with various assumed base-load capacity levels ranging from 40% to 100% of system peak load for representative U.S. electric systems are shown plotted in Figure 2. For a specific capacity level, the intersection of the capacity lines identifies points for which the amount of off-peak energy is equal to the on-peak energy. A curve identified as the 100% efficiency curve drawn through the points of intersection identifies for any system the maximum amount of on-peak energy that could be supported by the off-peak energy and the associated capacity level. For example, for system B, which has a 60% annual load factor, the maximum amount of supportable on-peak energy is approximately 10% of total energy produced for load and the associated capacity level is 73% of peak load as previously described.

This 100% efficiency on-peak/off-peak energy curve of Figure 2 also provides for the U.S. electric utility industry an estimate of the maximum amount of system on-peak energy capable of being supported by

off-peak energy. Since electric utilities with annual load factors falling in the 55-65% range represent about 80% of the total energy produced in the U.S.A., the maximum amount of on-peak energy that could be supplied by the so-called off-peak energy on U.S. electric utilities is estimated to be typically about 10% of the total annual energy produced for load.

For energy storage systems with overall efficiencies less than 100%, the maximum amount of on-peak energy that could be supported by off-peak energy would be reduced. Figure 2 shows this effect of lower energy storage system conversion efficiencies on supportable on-peak energy. For example, for a 60% annual load factor system and an energy storage system overall efficiency of 75 percent, the 11.5% available off-peak energy could support a maximum of only about 8.5% of the system on-peak energy requirements. In addition, to supply the required 11.5% off-peak energy, the assumed base-load capacity level of this system must be increased from the 73 to the 75% of peak load capacity level as shown in Figure 2.

The step-function profiles which were calculated for each day for each representative system and used as a basis for Figures 1 and 2 were also used to develop desirable operating characteristics for energy storage systems and to determine the amount of energy storage power capacity supportable on U.S. electric utilities. The results of these analyses are described below for system conditions representative of the maximum on-peak energy curve of Figure 2.

Off-Peak Energy

Off-peak energy as illustrated in Figure 1 on U.S. electric utilities was found to be relatively evenly distributed over the year on a seasonal, weekly, and daily basis.¹ As a percent of total annual off-peak energy, the typical seasonal, weekly, and weekday distribution of off-peak energy is

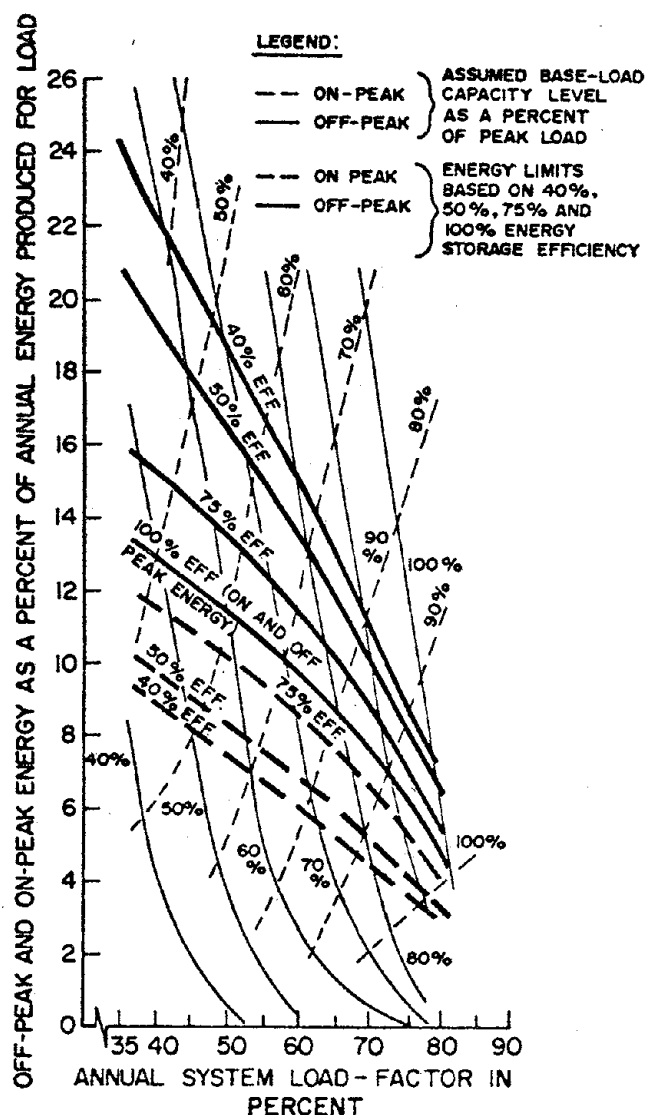


Fig. 2 Total Annual Off-Peak and On-Peak Energy Limits for U.S. Electric Utility Systems As Functions of Assumed Base-Load Capacity Level and Energy Storage System Efficiency

approximately 25%, 2%, and 0.2% respectively. The weekly energy was found to be divided between the five weekdays and the weekend on a 55/45 percentage split. More off-peak energy was found to be available on an average Sunday than on an average Saturday and each have more off-peak energy than an average weekday. About 0.4% of total off-peak energy was found to be available on a typical Saturday while 0.5% is more representative of Sunday's off-peak energy.

Table I summarizes the results of the off-peak energy and load profile analysis on U.S. electric utilities. It shows the weighted (according to system annual load factor distribution) average off-peak energy valley magnitudes and duration ranges on a summer peaking, winter peaking and combined system basis. The magnitudes of the off-peak energy valleys are shown to be somewhat larger for the summer peaking systems than for the winter peaking systems on both the

weekdays and weekends. The magnitude in all cases was found to be greatest on Sunday.

Table I shows that the off-peak energy available on U.S. electric systems on an average weekday has a duration range extending from 5 to a maximum of about 9 hours. For the weekend period, the duration ranges were found to be slightly longer for the summer peaking systems than for the winter peaking systems. On a combined basis, the off-peak energy durations on weekends extend from 14 up to a maximum of about 34 hours.

TABLE I
OFF-PEAK ENERGY
CHARACTERISTICS OF U.S.
ELECTRIC UTILITY SYSTEMS

Off-Peak Energy Profile Characteristics	Average Weekday	Average Weekend Saturday	Average Weekend Sunday
Summer Peaking Magnitude (%) ^a	13.5±2.2	16.0±3.4	19.1±4.3
Duration (hrs)			
Maximum	8.9±0.2	17.6±0.9	19.7±1.3
Minimum	5.1±0.5	6.7±1.0	6.7±1.2
Winter Peaking Magnitude (%) ^a	9.6±0.9	9.9±1.4	13.9±1.5
Duration (hrs)			
Maximum	8.7±2.3	11.1±2.8	17.5±1.1
Minimum	5.7±0.9	6.7±2.4	7.7±2.4
Combined Magnitude (%) ^a	11.9±2.9	13.8±4.1	17.3±4.4
Duration (hrs)			
Maximum	8.8±1.4	15.3±3.6	18.9±1.7
Minimum	5.3±0.7	6.7±1.6	7.1±1.8

a) Percent of system annual peak load.

On-Peak Energy

For the maximum on-peak energy conditions of Figure 2, the distribution of on-peak energy as a percent of total annual on-peak energy is about 25%, 2% and 0.35% on a seasonal, weekly and weekday basis respectively. The amount of on-peak energy required on a Saturday or Sunday was found to be almost negligible. The percentage ratio of on-peak energy requirements on weekdays to the on-peak energy requirements on weekends was observed to be about 93 to 7 percent.

Table II shows the weighted average load magnitude and duration of the on-peak energy intermediate loads for summer peaking and winter peaking systems and on a combined basis. The magnitude of the intermediate load was found to be approximately 9% of system annual peak load. The durations of the intermediate loads fall in a range from 9-14 hours per day each weekday of the year. Durations of 9-14 hours per day represent from 2300 to 3600 hours of operation on an annual basis.

The weighted maximum and average magnitudes of the peaking load portion of the on-peak energy requirements, shown in Figure 1 for system B as 23 percent, are shown in

Table III for the U.S. electric utilities on a summer peaking, winter peaking, and combined basis. On the average for any system, the maximum magnitude of the peaking load portion of the on-peak energy amounts to approximately 27% of the system annual peak load.

TABLE II
ON-PEAK ENERGY INTERMEDIATE LOAD
CHARACTERISTICS OF
U.S. ELECTRIC SYSTEMS

On-Peak Energy Profile Characteristics	Average Weekday	Average Weekend
Summer Peaking		
Magnitude (%) ^a	9.1±0.5	Negligible
Duration (hrs)		
Maximum	14.1±0.5	"
Minimum	10.1±0.3	"
Winter Peaking		
Magnitude (%) ^a	8.6±1.5	Negligible
Duration (hrs)		
Maximum	14.0±0.0	"
Minimum	8.4±1.5	"
Combined		
Magnitude (%) ^a	9.0±1.0	Negligible
Duration (hrs)		
Maximum	14.1±0.4	"
Minimum	9.5±1.2	"

a) Percent of system annual peak load.

TABLE III
ON-PEAK ENERGY PEAKING LOAD
CHARACTERISTICS OF U.S.
ELECTRIC UTILITY SYSTEMS

Peak Load Season	Magnitude (Percent of Peak Load)	
	Maximum	Average
Summer	28.0 ± 10.6	10.1 ± 2.4
Winter	24.4 ± 8.7	10.9 ± 4.2
Combined	26.8 ± 10.1	10.4 ± 3.1

An analysis of the frequency of occurrence of the peaking load durations was made by analyzing the peaking portion of the load shapes of the representative systems in load steps of 3% of annual system peak. Although peaking load durations of up to 16 hours were observed, approximately 80% of the peak load durations were less than 9 hours. The analysis also showed that energy storage devices serving this system application would be required to operate in a range from 250 to 2000 hours per year.

DUTY CYCLE CHARACTERISTICS

The above detailed analysis of the magnitude, duration and frequency of occurrence of the available off-peak energy and the on-peak energy requirements were used to develop duty cycles parameters for energy storage systems applicable on U.S. electric utility systems.

Duty Cycle Types

In general, there are three possible energy storage duty cycles that can be considered for the electric utility application: daily, weekly and seasonal.

The daily cycle is the simplest cycle and is based on charging the energy storage system with the off-peak energy available on an average weekday (or any 24 hour period) and discharging that same capacity during the following weekday on-peak period. Daily cycle energy storage systems require storage capability in hours equal to the discharge time. The daily cycle is limited to using only the off-peak energy available on weekdays or about 55 percent of the off-peak energy available on an annual basis.

The weekly cycle concept is simply an extension of the daily cycle to include the use of the off-peak energy available on the weekend for charging which will provide either longer discharge durations (hours) or greater discharge capacity (MW). The weekly cycle has the potential of utilizing most of the available annual off-peak energy. However, the weekly cycle requires energy storage systems with storage capability in the order of 2 or more times the storage capability required by the daily cycle.

Several variations exist for the so-called seasonal cycle. For example, off-peak energy might be stored all year long and discharged only during the peak season (Winter or Summer). Another possibility might be to store off-peak energy over only one off-peak season for use during the next peaking season. In general the storage requirements would be extremely large for any type of seasonal cycle.

The very even distribution of both off-peak and on-peak energy on a daily and weekly basis throughout the year favors the application of energy storage systems designed to operate on the daily or weekly cycle rather than the seasonal cycle. The fact that nearly one-half (45%) of the off-peak energy is generally available on weekends provides a strong incentive for application of energy storage systems designed to operate on the weekly cycle. The four typical energy storage system duty cycles analyzed for utility application are defined as follows:

- 1) Intermediate Generation System Application
 - a) Daily cycle
 - b) Weekly cycle
- 2) Peaking Generation System Application
 - a) Daily cycle
 - b) Weekly cycle

Typical Duty Cycle Parameters

For the system conditions representative of the maximum on-peak energy curve of Figure 2, Table IV summarizes the possible ranges of duty cycle operating parameters for energy storage systems with a 75% overall efficiency capable of being supported on U.S. electric utility systems.

The charge and discharge times of Table IV include those ranges of hours which were described in the previous on-peak and off-peak energy sections as being typical for the U.S. electric utility industry. All energy storage systems based on various efficiencies capable of operating within the range of combinations of charge and discharge time periods of Table IV are technically suitable for application on electric utility systems. However, these storage systems must also be economically attractive compared to alternate forms of generation for supplying intermediate and peaking system load requirements to be suitable for application on U.S. electric utility systems.

Table IV shows that for the intermediate duty application with the daily cycle, the C/D power ratios range from a low of 1.3, for energy storage capacity with a 9 hour discharge capability coupled with a 9 hour charge capability, to a high value of 3.7 for capacity with a 14 hour discharge and 5 hour charge capability. The storage capability limits are equal to the discharge capability limits for the daily cycle mode of operation. For the weekly cycle, the C/D power ratios are less than those of the daily cycle because of the additional charging time available on the weekend. The C/D ratio ranges from 0.8 for a 9 hour discharge and the maximum equivalent 16 hour charge capability to 2.4 for a 14 hour discharge capability and an 8 hour charge period. Storage capabilities range from 17 hours to 47 hours for the weekly cycle.

For the peaking duty application the 9 hour duration discharge is shown as the upper limit because the more frequently occurring on-peak energy requirement load durations were found to exist below this duration interval. Table IV shows for the peaking application with the daily cycle, the C/D power ratios range from 0.15 for a 1 hour

discharge coupled with a 9 hour charge period to 2.4 for a 9 hour discharge and 5-hour charge capability. The C/D ratio limits for the weekly cycle extend from 0.1, for a 1 hour discharge coupled with a weekly 16 hour equivalent charge time, to 1.5 for a 9 hour discharge and 8 hour equivalent charge time. The storage capability varies over a range from 2 to 30 hours. The method used to calculate the annual hours of operation shown in Table IV for the intermediate duty application and for the peaking duty application was previously described in the on-peak energy section.

The methods, including examples, for calculating charge to discharge power ratios and associated storage capability requirements are described in the Appendix. In addition, an indication of the spectrum of duty-cycle parameters that exist within the limits shown in Table IV are discussed in the following sections.

Charge/Discharge Power Ratio

Figure 3 shows the C/D power ratio for energy storage systems as a function of discharge time and charge time based on overall energy storage system efficiencies of 50%, 75% and 100%. The lines radiating from the origin represent combinations of discharge and charge times that would require the same C/D power ratio. As the efficiency decreases the C/D power ratio increases linearly which means for any specific discharge and charge time combination more charging power (MW) must be provided. Note that except for the 100% efficiency case the charge time must always be longer than the discharge time for a C/D power ratio of 1.0.

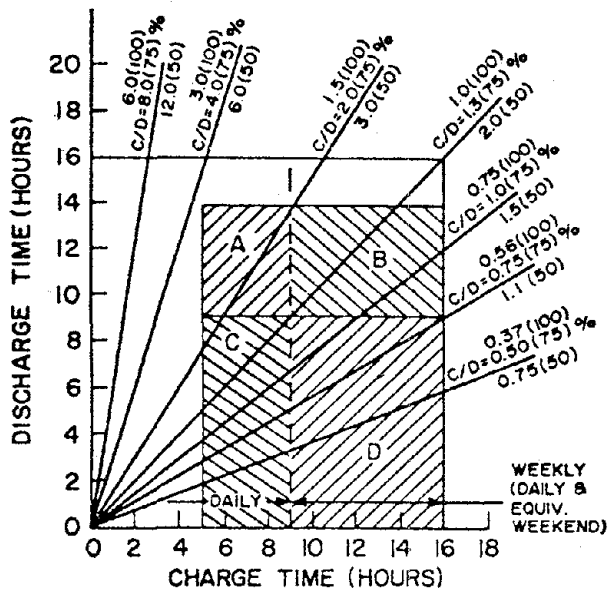
The limits of 16 hours represent the maximum discharge hours and charge hours associated with the U.S. electric system

TABLE IV
RANGES OF DUTY CYCLE OPERATING PARAMETERS
FOR ENERGY STORAGE SYSTEMS WITH 75%
EFFICIENCY SUPPORTABLE ON U.S.
ELECTRIC UTILITY SYSTEMS

Duty Cycle Characteristics	Type of Operation			
	Intermediate Duty		Peaking Duty	
	Daily Cycle	Weekly Cycle	Daily Cycle	Weekly Cycle
Discharge time (hrs/day)	9-14	9-14	1-9	1-9
Charge time (hrs/day)				
Weekday	5-9	5-9	5-9	5-9
Weekend	—	14-34	—	14-34
(Weekday equivalent of weekend)	—	(3-7)	—	(3-7)
Charge/Discharge Power Ratio	1.3-3.7	0.8-2.4	0.15-2.4	0.1-1.5
Storage Capability (Hours)	9-14	17-47	1-9	2-30
Annual Operation (Hours) (Annual Discharge time)	2300-3600	2300-3600	250-1000	250-1000

average on-peak and off-peak energy durations as previously defined. The diagonal of the square represents those efficiency and time combinations where the discharge time is equal to the charge time. The vertical dashed line at the 9 hour charge interval represents the break between the daily cycle and weekly cycle. It was assumed that any daily charging requirement over the 9 hours generally available on a weekday will require use of off-peak energy available on the weekends. Weekend charge time can be converted to equivalent weekday charge time by dividing the weekend charge time by five. Figure 3 represents weekday charge time and equivalent weekly charge time.

From Figure 3 all possible energy storage C/D power ratios that could be accommodated on U.S. electric utility systems can be identified for the peaking and intermediate duty system applications for both the daily and weekly cycle mode of operation. Figure 3 also provides the means of identifying the ranges of discharge and corresponding charge times for a specific C/D power ratio or any limiting C/D power ratio band width. It must be recognized, however, that some of these combinations would not be practical nor economic. The shaded regions of Figure 3 identify the approximate typical duty cycle charge to discharge power ratios shown in Table IV.



LEGEND:

- Area A = Intermediate duty, daily cycle
- " B = Intermediate duty, weekly cycle
- " C = Peaking duty, daily cycle
- " D = Peaking duty, weekly cycle

Fig. 3 Charge/Discharge (C/D) Power Ratios As A Function of Daily Charge Time and Daily and Weekly Charge Time Based on 100%, 75% and 50% Efficiency of Conversion

Storage Capability

Figure 4 provides an indication of the storage capability required of energy storage systems for any given discharge duration and

associated C/D power ratio (as previously shown in Figure 3) based on an energy storage system efficiency of 75%. The curves shown represent constant storage capability in hours - "isohours". Figure 4 can also be used to determine storage capability ranges for any C/D power ratio limits or band widths. It also contains combinations which may not be practical or economic.

The vertical sections of the "isohour" curves represent the daily cycle mode of operation. For the daily cycle the storage capability of energy storage systems must equal the discharge durations regardless of the C/D power ratio (or charge time). The lower curved portion of these "isohour" lines applies to the weekly cycle. They show for the weekly cycle that for any given discharge time the storage capability requirement increases to a limit as the C/D power ratio decreases. Similarly, for any fixed C/D power ratio as the discharge capability increases the required storage capability increases. As an example, Figure 4 shows for a 10 hour discharge device with a C/D power ratio of 1.0 that the storage requirement would be in the order of 22 hours based on a weekly cycle.

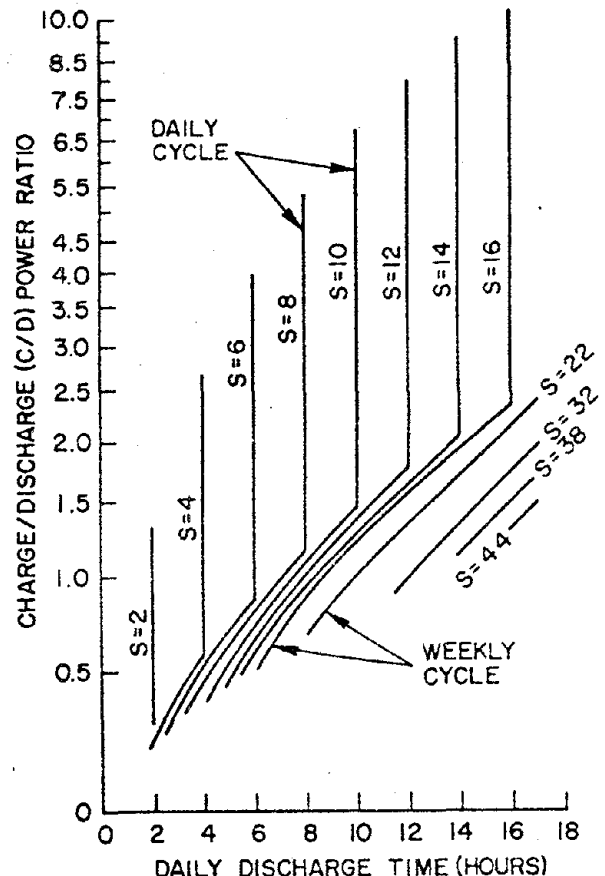


Fig. 4 Daily and Weekly Duty Cycle Storage Capability (Hours) As A Function of Daily Discharge Time and Charge/Discharge Power Ratio for a 75% Energy Storage System Efficiency

With a slight modification, Figure 4 can be used to determine the storage requirements of energy storage systems with different efficiencies by multiplying the C/D power ratio (based on the new efficiency) by the factor (new efficiency/.75) and entering the curves. This is possible because for any given charge time and discharge time the C/D power ratio is a function of the energy storage system efficiency.

SUPPORTABLE CAPACITY

Power

The amount of energy storage system power capacity capable of being supported can be developed from an analysis of the energy and load profiles of the U.S. electric systems. Various amounts of power capacity can be supported depending on the system generation application, the duty cycle type, the assumed base-load capacity level and the energy storage system overall efficiency.

For the maximum system conditions as described for Figure 2, that is, the on-peak peaking and intermediate load requirements of Tables II and III with the off-peak energy availability of Table I, an estimate of the maximum amount of power capacity capable of being supported by U.S. electric systems is summarized in Table V in terms of peak load and installed capacity. The method of calculating these limits for the peaking application and the weekly duty cycle is illustrated in Table VI. Table VI shows that a range of various energy storage system designs would be required to make effective use of all (weekday and weekend) of the off-peak energy to supply the on-peak peaking load requirements. Tables similar to

Table VI can be easily developed for the other three operating modes of Table V.

TABLE V
MAXIMUM ENERGY STORAGE SYSTEM CAPACITY
(100% EFFICIENCY) CAPABLE OF BEING
SUPPORTED ON U.S. ELECTRIC
UTILITY SYSTEMS

Duty Cycle	System Application			
	Intermediate Duty		Peaking Duty	
	% of Peak Load	% of Installed Capacity	% of Peak Load	% of Installed Capacity*
Daily	8	6	14	11
Weekly	12	10	20	16

* Installed Capacity assumed to be 1.25 times peak load.

Table V indicates that more energy storage megawatt capacity can be supported on U.S. electric systems for the peaking application than for the intermediate application because of the generally shorter discharge times associated with the peaking mode. In addition, use of the weekly cycle substantially increases the amount of energy storage system power capacity capable of being supported for either the peaking or intermediate generation modes.

Energy

The maximum amount of on-peak energy requirements capable of being supported by available off-peak energy at a given base-load capacity level was shown in Figure 2.

TABLE VI

MAXIMUM ENERGY STORAGE SYSTEM CAPACITY (100% Efficiency)
CAPABLE OF BEING SUPPORTED ON U.S. ELECTRIC UTILITY SYSTEMS
FOR THE PEAKING GENERATION APPLICATION AND WEEKLY DUTY CYCLE

Supportable Capacity (% of peak load)	Daily Discharge Time (Hours)	Storage Capability (Hours)	Charging Hours		C/D Power Ratio
			Average Weekday	Average Weekend	
3.0	2	5.7	5	22	.21
3.0	4	11.5	5	22	.43
1.7	6	17.2	5	22	.64
1.3	6	17.1	6	26	.54
3.0	8	22.9	6	26	.71
0.2	10	28.6	6	26	.89
2.8	10	27.1	8	30	.71
1.2	12	32.6	8	30	.86
1.8	12	32.7	9	34	.76
1.8	14	38.1	9	34	.89

TOTAL 19.8%

ORIGINAL PAGE IS
OF POOR QUALITY

This estimate of the supportable energy was based on annual off-peak energy availability and on-peak energy load requirements neglecting daily distributions of the on-peak and off-peak energy. However, considering distribution, the practical amount of on-peak energy that could be supplied by the consistently available off-peak energy is somewhat less as shown in Figure 5.

The maximum limit is based on energy storage system efficiency of 100 percent. The practical limits which are also based on 100 percent energy storage efficiency were developed from analyses of the representative electric systems distribution of energy. The higher practical limit is based on the use of the weekly duty cycle whereby most of the annual off-peak energy is utilized to support on-peak energy requirements. If energy storage systems are limited to only daily duty cycles, the lower practical limit of Figure 5 would apply. With the daily duty cycle, less than half of the annual off-peak energy can be utilized to support on-peak energy requirements. For the U.S. electric systems, the maximum practical amount of on-peak energy capable of being supplied is therefore estimated for the weekly cycle to be 3 to 9% of the total energy produced for load.

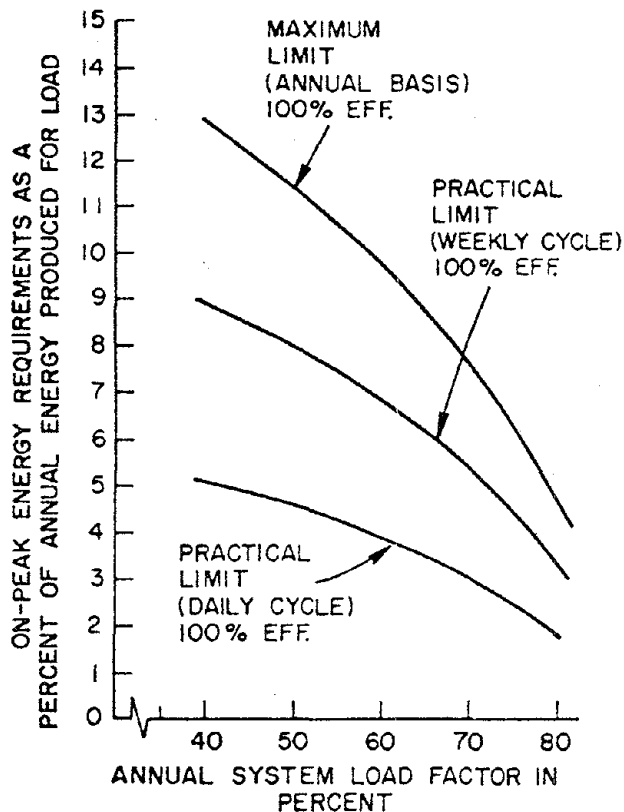


Fig. 5 Maximum and Practical Limits of On-Peak Energy Requirements Capable of Being Supplied by the Off-Peak Energy Available on U.S. Electric Utilities

CONCLUSIONS

Based on an analysis of U.S. electric systems consistent with conventional electric utility practices, it can be concluded that rechargeable energy storage capacity could play an important role in supplying future peaking and intermediate system load requirements. The distribution of both off-peak and on-peak energy on U.S. electric systems on a seasonal, weekly and daily basis was observed to be relatively evenly distributed which favors the application of energy storage systems capable of operating on a daily or weekly cycle.

Based on a 100% overall efficiency the maximum practical amount of installed energy storage power capacity capable of being supported by the off-peak energy available on U.S. electric systems was estimated to be approximately 20% of annual system peak load based on the weekly duty cycle. With only the daily cycle, the maximum amount was estimated to be approximately 14% of peak load. The maximum practical amount of on-peak energy that could be supplied by the potentially available off-peak energy was estimated to be approximately 3-9% of the total energy produced for load by electric utilities.

U.S. electric systems were found to possess extremely similar energy characteristics (magnitude and duration) which define a spectrum of desirable energy storage duty cycle parameters for the application of energy storage systems on electric utilities. The wide range of different combinations of duty cycle operating parameters based on both the daily and weekly cycle modes of operation for both intermediate and peaking generation applications should enable the application of a number of different types of energy storage technologies to U.S. electric systems.

APPENDIX

Charge/Discharge Power Ratio

The following equation shows the relationship between the discharge capacity and the charge capacity, the associated discharge and charge times and the energy storage system overall efficiency (electric to electric).

$$\text{ENERGY INPUT} \times e = \text{ENERGY OUTPUT}$$

$$C \times T_c \times e = D \times T_d$$

Where C = Charge Capacity (MW)
 D = Discharge Capacity (MW)
 T_c = Charge Time (hours)
 T_d = Discharge Time (hours)
 e = Energy Storage Overall Efficiency (%)
 (electric to electric)

The relationship between the charge and discharge capacity, the C/D power ratio, is then

$$\frac{C}{D} = \frac{T_d}{T_c \times e}$$

Assuming the desired discharge time of 10 hours and an allowable daily charge time of 9 hours, the required charge capacity would be 1.5 times the discharge capacity for an energy storage system with a 75% overall efficiency.

$$\frac{C}{D} = \frac{10}{9 \times .75} = 1.5$$

To apply the equation to develop C/D power ratios for the weekly cycle application, the charging time available over the weekend period should be allocated over the five weekdays and added to the daily charge time. Assuming the desired discharge time of 10 hours, an allowable daily charge time of 9 hours and a weekend charge capability of 15 hours, the required charge capacity would be 1.1 times the discharge capacity for any energy storage system with a 75% overall efficiency.

$$\frac{C}{D} = \frac{10}{(9 + 15/5) \times .75} = 1.1$$

Storage Capability

The storage capability (in hours) required of an energy storage system for the daily cycle is essentially the daily discharge duration as shown in the following equation.

$$T_d = \frac{C \times T_c \times e}{D} = S$$

Using the daily cycle previously described the required storage capability would be 10 hours.

$$S = \frac{1.5D \times 9 \times .75}{D} = 10$$

The storage capability must be greater for the energy storage system capable of operating on a full weekly cycle than for the daily cycle. The weekly storage capability must be large enough to hold a full weekend (Saturday and Sunday) charge in addition to a full weekday charge. The following equation describes this relationship.

$$S = \frac{C \times T_w \times e}{D}$$

Where S = Storage Capability (Hours)
C = Charge Capacity (MW)
T_w = Charge Time (Sat.+Sun.+Mon.) (Hours)
e = Energy Storage Overall Efficiency (%)

Using the weekly example given previously the required storage capability would be approximately 20 hours for the system described.

$$S = \frac{1.1D \times (9+15) \times .75}{D} = 19.8 \text{ Hours}$$

ACKNOWLEDGEMENTS

The results in this paper were developed in connection with a research project jointly sponsored by the Energy Research and Development Administration and the Electric Power Research Institute. The system analysis work was performed by the Public Service Electric and Gas Company. The authors wish to thank Messrs. R. A. Fisher and J. M. Torres for their assistance and Ms. M. T. Burger for her typing assistance.

REFERENCES

1. V. T. Sulzberger, J. Zemkoski, "The Potential for Application of Energy Storage Capacity on Electric Utility Systems in the United States - Part I," IEEE Transactions Paper, presented at the 1976 IEEE Winter Power Meeting, January 26-30, Published in "Energy Development-II" 76-CH-1102-3-PWR, IEEE publication.
2. W. Wood, M. P. Bhavaraju, S. J. Solowski, D. C. Widman, "A Probabilistic Approach to Off-Peak Electric Energy Evaluation," Paper F76 179-2, presented at the 1976 IEEE Winter Power Meeting, New York, January 26-30, 1976.

ORIGINAL PAGE IS
OF POOR QUALITY

APPENDIX 5-3

ELECTRICAL INTERFACE REQUIREMENTS

J. S. Pirrong
Public Service Electric and Gas Company

The establishment of the energy storage/utility system interface requirements necessitates the definition of the power system's characteristics and its permissible variations. The interface requirements may then be defined on the premise that the existing distribution systems must not be modified to accommodate the energy storage system. This approach to incorporating the energy storage system into the existing power system acknowledges that large capital investment exists in utility distribution equipment. With such large investment, modifications to the utility system would prove neither practical nor economic. The characteristics of the distribution system are not uniform from station to station nor constant at any given point. For instance, the distribution system could serve industrial, commercial or residential loads, or any combination of them. Similarly, any one substation's characteristics will change as new loads are added or existing loads are changed or eliminated. Hence, the characteristics of a utility's distribution system cannot be universally defined in great detail. Therefore, interface requirements must be sufficiently general to permit application into a distribution system that is constantly changing in configuration and load profile. Specification of parameters to incorporate the energy storage device at one particular location could restrict its use at other points in the distributing system. The following interface requirements are addressed:

- a. Voltage level
- b. Frequency
- c. Reactive Power Requirements
- d. Harmonics
- e. Radio Interference and Audible Noise
- f. Faults
- g. Auxiliary Power Requirements

Nominal values discussed below were obtained from various sources, and in all cases are representative of the Public Service distribution system. Application on other systems which could exhibit different characteristics might require modification of certain parameters.

It is anticipated that the energy storage device (ESD) will be installed at distribution substations. In general, there is no universal distribution voltage level in the U.S. Indeed, as load densities increase, distribution voltage levels have increased. Therefore, 4, 13, 26, and 34.5kV are all used as distribution levels in various areas of the country. The nominal voltage level at a Public Service substation is 13,800 volts line-to-line (796v line-to-neutral). The schematic of a fully developed substation is given in Figure 1. The ESD would be installed on the LV bus as shown.

Because automatic voltage regulation is installed on the substation bus, this bus voltage will not vary more than $\pm 2\%$. Therefore, the energy storage device must be designed to provide an essentially constant output voltage.

Also, if the voltage of the ESD was not sufficiently controlled, its voltage could influence the bus voltage and cause excessive operation of the automatic voltage control devices. These excessive operations would cause abnormal and objectionable amounts of maintenance.

In the U.S., the frequency of the distribution voltage is essentially constant, varying by ± 1 Hz about 60 Hz nominal value. Under abnormal conditions, substation bus voltage could collapse to near 0% or rise to 200% or more for several cycles (less than 0.1 seconds). Similarly, under highly abnormal and improbable conditions, the frequency could decrease to 58.5 Hz.

Although the energy storage system would inject only real power into the power system, the commutation process, transformers, filters, and other components of the dc to ac conversion device all impose reactive power requirements. At distribution voltage levels, the utility's ac system is not designed to accomodate the injection of large amounts of reactive power. Only about 2 MVAR, either capacitive or inductive, could be absorbed by the 13kV system.

Injection of harmonic currents into the ac system and consequential distortion of the ac voltage must be minimized. Excessive harmonics in the ac system has many adverse effects, including overheating of transformers and capacitors, production of errors in metering, interfering with ripple control systems such as used for time-of-day metering, and inducing interference in communication circuits. The last noted effect, interference with communication systems, is highly indeterminate on a general basis. Increasing use of shared right-of ways, and the subsequent closer coupling of power and telephone circuits, makes historical harmonic limits of questionable value. Increased use of telephone circuits for data transmission also imposes stricter limits on acceptable interference. Furthermore, distribution systems are by nature constantly changing in configuration. Therefore, what may be acceptable harmonic limits today, may not be in the future. However, if interference is found to be objectionable in a particular location, it can be economically rectified by filtering circuits added after the initial installation. All these factors make the specification of allowable harmonic limits arbitrary. Therefore, the highest allowable single harmonic voltage should be limited to 1%, and the sum of all harmonic voltages less than 3%.

Radio interference (RI) from the ESD must be minimized. The inversion process (dc to ac), which produces large voltage changes within a short time, generates a wide frequency of electromagnetic interference (EMI). The ESD should be designed and installed to limit the RI to 100 microvolts per meter (at 1Mhz) at the station property line. Installation of filters in the ac line feeds may also be necessary to correct EMI.

Distribution substations are installed in all environments: residential, commercial and industrial. Residential areas impose rigid audible noise requirements, both from a legal standpoint and a customer relation standpoint. Many municipalities have adopted noise ordinances which proscribe noise limits at the property line. Therefore, audible noise as measured at the property line must be minimized. PSE&G substations are designed to limit noise

to an average of 48dBA at the property line. This maximum noise value must be adhered to by the installed energy storage system.

For overvoltage protection, two principles must govern the application of the energy storage device. First, the dc equipment must be designed to withstand overvoltages existing in the ac system. Second, the energy storage device must not impose additional burdens on the ac equipment or its protection. PSE&G ac equipment is designed to have a basic impulse insulation level (BIL) of 110kV, protected by 10 kV distribution class surge arresters. The ac terminal of the storage device should also be designed to meet these requirements.

To meet the second requirement, overvoltages developed within the energy storage system must be attenuated so as not to affect the BIL or protective device requirements of the ac system. Care must be exerted so that dc equipment does not overstress ac protective devices. This is particularly true of capacitor installation, since surge arresters are severely limited in their ability to discharge capacitive current.

Present station design at 13kV is limited by the short circuit rating of equipment located outside the substation. This equipment is presently operating near its short circuit rating. Utilities spend large amounts of money to limit distribution level short circuit currents. Any increase in short circuit level of the distribution system is objectionable. Therefore, provision must be incorporated into the conversion device to limit short circuit current to less than 110% of rated current.

Finally, the auxiliary power requirements of the converter must be established to minimize its effect on the distribution system. For example, if the storage system required large induction motors, starting currents for these motors, which can be 600% of full load current, may cause objectionable voltage dips in the ac system. A system of this nature would require an auxiliary method of starting or a special starting circuit. Each ESD must be examined for such effects.

Summary

In summation, integration of energy storage devices into an electric distribution system must be made within the bounds of the parameters listed in Table 1.

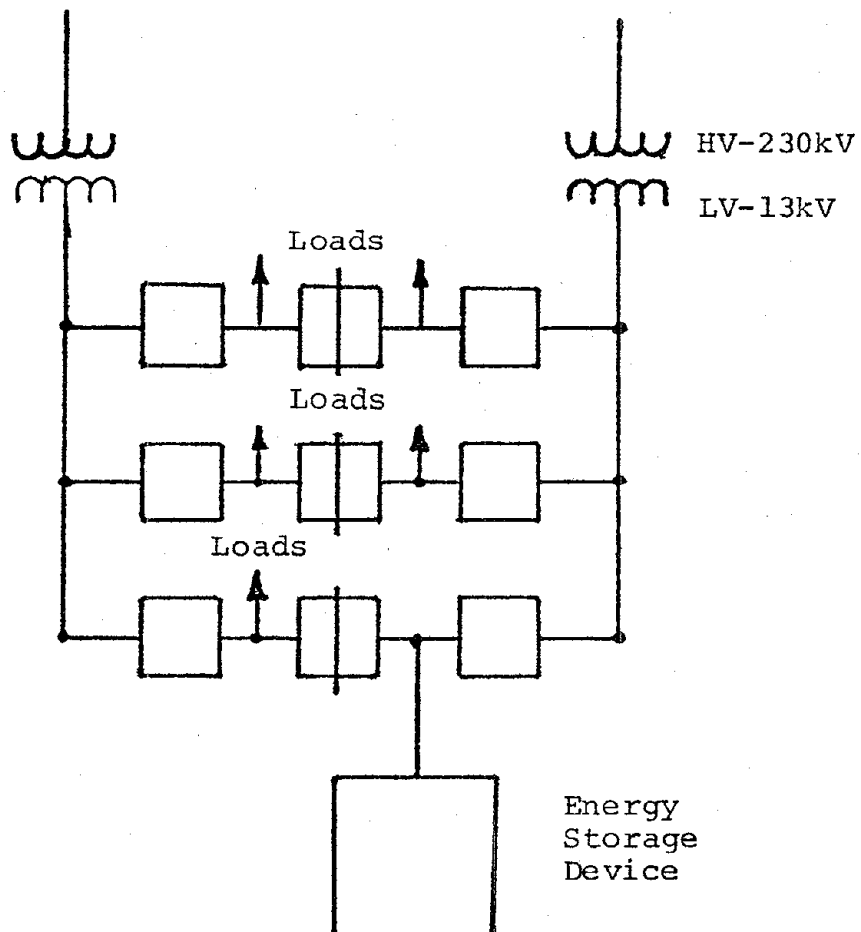
Table 1

Parametric Bounds for Integration of Energy Storage
Devices Into an Electric Utility Distribution System

<u>Parameter</u>	<u>Requirement</u>
Voltage (1-1)	13,800 V \pm 2%
Frequency	60 Hz \pm 0.1 Hz
Reactive Power Exchange with AC System	\pm 2 MVAR
Harmonics	
+ Maximum Single Voltage	< 1%
+ Maximum Total Voltage	< 3%
Radio Interference	< 100 microvolts @ 1 MHz
Audible Noise at Property Line	< 48 dBA
Basic Impulse Insulation Level (BIL)	110 kV
+ Surge Arresters	10 kV
Short Circuit Current Limit	< 110% of Rated Current

Figure 1

Schematic of Fully-Developed Sub-Station



APPENDIX 5-4

SELECTED BIBLIOGRAPHY OF ELECTROCHEMICAL DESIGN REFERENCES

A. Manifold Distribution

1. Van der Hegge Zijnen, B.G., "Flow through uniformly tapped pipes", App. Sci. Res. A3 144 (1951-1953).
2. Senecal, V.E., "Fluid distribution in process equipment" IEC 49 993 (1957).
3. Litz, W.J., "Design of gas distributors", Chem. Eng. Nov. 13, 1972, p. 162.
4. Grobman, J.S., et al., "Pressure drop and air-flow distribution in gas-turbine combustors", Tr. ASME, October, 1957, p. 1601.
5. Stoker, R.L., "Methods of producing uniform velocity distribution", IEC 38 622 (1946).
6. Sisson, W., "Sizing pipe manifold systems", Plant Engineering, 27 (26) 50 (1973).
7. Mikhailov, V.S., et al., "Investigation and calculation of hydrodynamics of distributing and collecting headers", Thermal Engineering (USSR) 21 60 (1974).
8. Bailey, B.J., "Fluid flow in perforated pipes", J. Mech. Eng. Sci 17 338 (1975).
9. University of Minnesota and Honeywell, Sections in a series of reports entitled, "Research Applied to Solar-Thermal Power Systems",
Report NSF/RANN/SE/GI - 34871/PR/73/2 (July 31, 1973) p. 173
" " /73/4 (January 31, 1974) p. 3-155
" " /74/2 (July 31, 1974) p. 3-87
10. Koshel, N. et al., "Operation of multicell electrochemical systems with flow-type electrolytes". I. Laminar circulation", Elektrokimiya 9 216 (1973).

B. Shuntage Current

1. Frie, W., "Power losses from leakage in fuel cell aggregates", Chem. Ing. Tech 42, 1081 (1970).
2. Onishchuk, V.A., "Optimization of the electrical parameters of an electrochemical multivoltage battery as a function of the electrolyte feed circuit", Soviet Electrochemistry 8 681 (1972).
3. Union Carbide, "Analysis of leakage currents in fuel cell batteries", Section in Carbon Electrode Fuel Cell, Report No. ASD-TDR-62-1044, (AD-403890), p. 83, (March, 1963).

4. Yakimenko, L.M., et al., "Determination of leakage currents in bipolar cells for production of hydrogen and oxygen and their influences on specific energy consumption", J. Appl. Chem. (USSR) 44, 1310 (1971).
5. Chiku, T., "Electrolyte circulating battery", U.S. Patent No. 3,666,561 (May 30, 1972).
6. Yauch, D.W., "A differential current metering system for location and measurement of leakage currents in high current DC electrolyte cell line circuits", IEEE Trans. Ind. Appl. IA-11, 457 (1975).
7. Nesterov, B.P., et al., "Dispersion currents in filter press type batteries with a common collector", Soviet Electrochemistry 9, 1091 (1973).
8. Ksenzhek, O.S. and Koshel, N.D., "Current leakage in high-voltage batteries", Parts I, II and III, Soviet Electrochemistry 6, 1531 (1970); 7, 331, 820 (1971).
9. Rousar, I. and Cezner, V., "Experimental determination and calculation of parasitic currents in bipolar electrolyzers with application to chlorate electrolyzer", J. Elec. Soc. 121, 648 (1974).
10. Forster, A.G., "Cell shocks - Not necessary in chlorine cell rooms", IEEE Trans. Ind. Appl. IA-11, 716 (1975).
11. Solt, G.S., "Leakage currents in electrodialysis", AlChE-ICChE Symposium Series No. 9, 9:9, 1965.
12. Mandersloot, W.G.S. and Hicks, R.E., "Leakage currents in electrodialytic desalting and brine production", Desalination 1, 178 (1966).
13. Prokopius, P., "A model for calculating the electrolytic path losses in large electrochemical energy conversion systems", NASA-Lewis Research Center, Paper E-8501 (Advance Copy-to be published).
14. Rousar, I., "Calculation of current density distribution and terminal voltage for bipolar electrolysis; Application to chlorate cells", J. Elec. Soc. 116, 676 (1969).

C. Current Collection

1. Gorin, E. and Recht, H.L., "Fuel cells", CEP 55 (8) 51 (1959).
2. Gorin, E. and Recht, H.L., "High temperature fuel cells", Chapter 5 in Fuel Cells, W. Mitchell, Jr., ed., Academic Press, New York, 1963, p. 193 (p. 226).
3. Gorin, E. and Recht, H.L., "Nature of the electrode process", IEC 52 306 (1960).
4. Gorin, E. and Recht, H.L., "Nature of the electrode processes in fuel gas cells", Chapter 8 in Fuel Cells, G. J. Young, ed., Reinhold, New York, 1960, p. 109.

5. Eisenberg, M. and Fick, L., "Potential distribution and internal resistance in electrochemical matrix cells with discontinuous contacts", Chapter 9 in Fuel Cells, Volume 2, G. J. Young, ed., Reinhold, New York, 1963, p. 113.
 6. Fick, L. and Eisenberg, M., "Fuel cell analysis", CEP 57 (5) 74 (1961).
 7. Eisenberg, M., "Design and scale-up considerations for electrochemical fuel cells", Chapter 5 in Advances in Electrochemistry and Electrochemical Engineering, C.W. Tobias, ed., Interscience, New York, 1962, p. 275.
 8. Beltzer, M. and Horowitz, H.H., "Surface resistivity problems in thin electrodes", Electrochem Tech. 4 464 (1966).
 9. Zaromb, S., "Geometric requirements for uniform current densities at surface conductive insulators or resistive electrodes", J. Elec. Soc. 109, 912 (1962).
 10. Wagner, C., "Theoretical analysis of the current density distribution in electrolytic cells", J. Elec. Soc. 98, 116 (1951).
 11. Zdorov, I.P., et al., "How to determine current collection efficiency of fuel cell electrodes by mathematical simulation". Meas. Tech. (USSR) 15, 930 (1972).
 12. Meerovich, I.G. and Kononova, G.A., "Effect of ohmic losses on the current distribution in a fuel cell", Soviet Electrochemistry, 10, 292 (1974).
- D. Electrochemical Engineering
1. Newman, J.S., Electrochemical Systems, Prentice-Hall, Englewood Cliffs, New Jersey, 1973.
 2. Austin, L.G., "The electrochemical theory of fuel cells", Chapter in Handbook of Fuel Cell Technology, C. Berger, ed., Prentice-Hall, Englewood Cliffs, New Jersey, 1968, p. 1.
 3. Vetter, K.J., Electrochemical Kinetics, Academic Press, New York, 1962.
 4. Levich, V.G., Physicochemical Hydrodynamics, Prentice-Hall, Englewood Cliffs, New Jersey, 1962.
 5. Palade de Iribarne, A., et al., "Ionic mass transfer in chemical electrodes under laminar flow", Elec. Acta 15, 1823 (1970).
 6. Newman, J., "The effect of migration in laminar diffusion layers", Int. T. Heat Mass Transfer 10, 983 (1967).
 7. Parrish, W.R. and Newman, J., "Current distributions on plane, parallel electrodes in channel flow", J. Elec. Soc. 117, 43 (1970).
 8. Ibid., "Current distribution on a plane electrode below the limiting current", J. Elec. Soc. 116, 169 (1969).

9. Tobias, C.W. and Hickman, R.G., "Ionic mass transport by combined free and forced convection", *Z. Phys. Chem. (Leipzig)* 229, 145 (1965).
10. Eisenberg, M., et. al., "Ionic mass transfer and concentration polarization at rotating electrodes", *J. Elec. Soc.* 101, 306 (1954).
11. Ibl, N. and Muller, R.M., "Studies of natural convection at vertical electrodes", *J. Elec. Soc.* 105, 346 (1958). Also, comments by G. Wranglen, *J. Elec. Soc.* 106, 536 (1959).
12. Wragg, A.A., "A note on electrochemical mass transfer from flowing solutions to cylindrical electrodes", *Elec. Acta.* 20, 917 (1975).
13. Ross, T.K. and Wragg, A.A., "Electrochemical mass transfer studies in annuli", *Elec. Acta* 10, 1093 (1965).
14. Arvia, A.J. and Marchiano, S.L., "Transport phenomena in electrochemical kinetics", Chapter 3 in *Modern Aspects of Electrochemistry*, No. 6, J. O'M. Bockris and B. E. Conway, eds., Plenum Press, New York, 1971, p. 159.
15. Elder, J.P. and Wranglen, G., "Mass transfer at plane plate electrodes", *Electrochem Tech.* 2, 34 (1964).
16. Wranglen, G., and Nilsson, O., "Mass transfer under forced laminar and turbulent convection at horizontal plane plate electrodes", *Elec. Acta* 7, 121 (1962).
17. Tobias, C.W., et. al., "Diffusion and convection in electrolysis - A theoretical review", *J. Elec. Soc.* 99, 359C (1952).
18. Wranglen, G., "Mass transfer by laminar free convection at vertical electrodes", *Acta Chem. Scand.* 12, 1143 (1958).
19. Ibid, "Mass transfer by forced laminar convection at plane plate electrodes", *Acta Chem. Scand.* 13, 830 (1959).
20. Pickett, D.J. and Stanmore, B.R., "Studies on the design and operation of continuous flow parallel plate electrochemical cells", *Inst. Ch.E. (London) Symp. Ser. No. 37, Electrochemical Engineering*, 1971, p. 1.16.
21. Ibid, "Ionic mass transfer in parallel plate electrochemical cells", *J. Appl. Electrochem.* 2, 151 (1972).
22. Pickett, D.J., "The analysis of an isothermal batch electrochemical reactor with a secondary cathodic reaction", *Elec. Acta.* 19, 239 (1974).
23. Pickett, D.J. and Ong, K.L., "The influence of hydrodynamic and mass transfer entrance effects on the operation of a parallel plate electrolytic cell", *Elec. Acta.* 19, 875 (1974).
24. Pickett, D.J., "Design and operational aspects of flow cells for electrowinning purposes", *Chem and Ind.*, No. 8, April 19, 1975.

25. Feldberg, S.W., "Digital simulation: A general method for solving electrochemical diffusion-kinetic problems", Chapter in Electroanalytical Chemistry, Vol. 3, A.J. Bard, ed., Marcell Dekker, New York, 1969, p. 199.
26. Klingert, J.A., et. al., "Evaluation of current distribution in electrode systems by high-speed digital computers", Elec. Acta. 9, 297 (1964).
27. Gerischer, H., et. al., "Electrolyse in Stromungskanal", J. Electroanal. Chem. 10, 553 (1965).
28. Vielstich, W., "Der Zusammenhang Zwischen Nernstscher Diffusionsschicht und Prandtlscher Stromungsgrenzschicht", Z. fur Elektrochem. 57, 646 (1953).
29. Kumar, P.A., et. al., "Ionic mass transfer at electrodes of rectangular and square cross-sections in transverse flow", Indian J. Tech. 12, 229 (1974).
30. Jaksic, M.M. and Nikolic, B.Z., "The fundamentals of optimum design of chlorate cells. I, II", Chem. Techn. 27, 158, 534 (1975).
31. Lin, C.S., et. al., "Diffusion-controlled electrode reactions", IEC 43, 2136 (1951).
32. Eisenberg, M., "Design and scale-up considerations for electrochemical fuel cells", Chapter 5, in Advances in Electrochemistry and Electrochemical Engineering, Vol. 2, C.W. Tobias, ed., Interscience, New York, 1962 p. 275.
33. Ibl, N., "The formation of powdered metal deposits", Chapter 3 in Advances in Electrochemistry and Electrochemical Engineering, Vol. 2, C. W. Tobias, ed., Interscience, New York, 1962, p. 49.
34. Beronius, P., "Effect of solvent viscosity on boundary layer in electrode processes", J. Electroanal. Chem. 27, 458 (1970).
35. Dworak, R. and Wendt, M., "Hydrodynamics and mass transfer within cylindrical capillary gap electrolysis cell", Berichte Bunsen-Gesell. 80, 77 (1976).
36. Despic, A.R., et. al., "The effect of kinetic and hydrodynamic factors on current efficiency in the chlorate cell process, " J. App. Electrochem. 2, 337 (1972).
37. Donahue, F.M., "Design of iso-thermal electrochemical reactors", Abstract No. 262, Electrochem Soc., April, 1970, p. 630.
38. Wilke, C.R., et. al., "Free-convection mass transfer at vertical plates", Ch. Eng. Prog. 49, 663 (1953).
39. Ibid., "Correlation of limiting currents under free convection conditions", J. Elec. Soc. 100, 513 (1952).

40. Eisenberg, M., "Some principles of electrochemical fuel cell design", *Elec. Acta.* 6, 93 (1962).
41. Gridelli, R., "Diffusion toward planer, spherical and dropping electrodes at constant potential", *J. Electroanal Chem.* 33, 291, 302 (1971).
42. Ibl, N., "Probleme des Stofftransportes in der angewandte elektrochemie", *Chem. Ing. Tech.* 35, 353 (1963).
43. Schalch, E. and Ibl, N., "Mass transfer at wiped plates", *Elec. Acta.* 20, 435 (1975).
44. Robertson, P.M., et. al., "A new cell for electrochemical processes", *J. Electroanal Chem.* 65, 833 (1975).
45. Ibl, N., and Braun, M., "Role of mass transfer in electrolysis of metals", *Ch. Ing. Tech.* 45, 182 (1973).
46. Kuhn, A.T. and Marquis, B., "The performance of a fixed-flow parallel plate electrochemical reactor with dilute solutions", *J. Appl. Electrochem.* 2, 275 (1972).
47. Newman, J., "Engineering design of electrochemical systems", *IEC* 60, (4) 12 (1968).
48. Ibid., "Effect of ionic migration on limiting currents", *IEC Fund* 5, 525 (1966).
49. Ibid., "Transport processes in electrolytic solutions", Chapter in Advances in Electrochemistry and Electrochemical Engineering, Vol. 5, C.W. Tobias, ed., Interscience, New York, 1967, p. 87.
50. Selman, J.R. and Newman, J., "Free convection mass transfer with a supporting electrolyte", *J. Elec. Soc.* 118, 1070 (1971).
51. Oldham, K.B. and Spanier, J., "The replacement of Fick's laws by a formulation involving semi-differentiation", *J. Electroanal Chem.* 26, 331 (1970).
52. Rodionova, T.M., et. al., "Dependence of mass transfer to the electrode on convective conditions", *J. Appl. Chem. USSR* 44, 1281 (1971).
53. Ruo, A.S., "Problem of scale-up in electrochemical systems", *J. Appl. Electrochem* 4, 87 (1974).
54. Rousar, I., et. al., "Limiting local current densities for electrodes located on the walls of a rectangular channel with laminar flow; Asymptotic solution and experimental verification", *J. Elec. Soc.* 118, 831 (1971).

55. Richard, M.C., "Use of a mathematical cell model to determine cell parameter design changes for production maximization", Light Metal (AIME), 1975, p. 95.
56. Ali, M.S. et. al., "Performance of a bi-polar thin film cell for chlorate production", Elec. Acta. 21, 159 (1976).
57. Mohanta, S. and Fahidy, T.Z., "Ionic mass transfer in open channel flow", Elec. Acta. 21, 143 (1976).
58. Yuodkazis, K.I. and Vishomirskis, R.M., "The question of mass transfer in flowing electrolytes", Soviet Electrochemistry 11, 633 (1975).
59. Ibl, N., "The use of dimensionless groups in electrochemistry", Elec. Acta. 1, 117 (1959).
60. Jennings, D., et. al., "A mass transfer study of two-phase flow in an electrochemical reactor", Elec. Acta. 20, 903 (1975).
61. Tvarusko, A., "Dimensionless correlation of mass transfer in wire electroplating cells of various designs", J. Elec. Soc. 120, 87 (1973).
62. Tobias, C.W., New directions in electrochemical engineering", J. Elec. Soc. 120, 65C (1973).
63. Wragg, A.A., "Combined free and forced convective ionic mass transfer in the case of opposed flow", Elec. Acta. 16, 373 (1971).
64. Koshel, N.D., et. al., "Operation of multicell electrochemical systems with flow-type electrolytes. I. laminar circulation; II square-law resistance region", Elektrokhiimiya 9, 216 (1973); 10, 1356 (1974).
65. Ibid., "Multicell electrochemical systems with a circulating electrolyte under non-steady-state operating conditions", Elektrokhiimiya 10, 1149 (1974).
66. Ibid., "Determination of the steady-state parameters in an electrochemical system with separated electrode compartments", Elektrokhiimiya 11, 368 (1975).

E. Electrodialysis Desalination

1. Mandersloot, W.G.B. and Hicks, R.E., "Concentration polarization on ion exchange membranes in electrodialytic demineralization", IEC Proc. Des. Dev 4 304 (1965).
2. Pnevli, D. and Grossman, G., "A mathematical model for the concentration field in an electrodialysis cell", Desalination 7 297 (1970).

3. Spiegler, K.S., "Polarization at ion exchange membrane-solution interfaces", Desalination 9 367 (1971).
4. Belfort, G. and Guter, G.A., "An electrical analogue for electro-dialysis", Desalination 5 267 (1968).
5. Ibid., "An experimental study of electrodialysis hydrodynamics", Desalination 10 221 (1972).
6. Solan, A., et. al., "An analytical model for mass transfer in an electrodialysis cell with spacer of finite mesh", Desalination 9 89 (1971).
7. Solt, G.S., "Influence of membrane phenomena on electrodialysis operation", Proc. First Int'l. Symp. Water Desalination, Washington, D.C., October 3-9, 1965, Vol. 2, p. 13.
8. Cooke, B.A., "Some phenomena associated with concentration polarization in electrodialysis", Ibid., Vol. 2, p. 219.
9. Matz, R., "Electrodialysis-pilot plant and general development", Proc. First Int'l. Symp. Water Desalination, Washington, D.C., October 3-9, 1965, Vol. 2, p. 251.
10. Klyachko, V.A., et. al., "Desalination of saline water by electrolysis-selection of optimum current density", Proc. First Int'l. Symp. Water Desalination, Washington, D.C., October 3-9, 1965, Vol. 2, p. 511.
11. Corning, D.R., "Electrodialysis using ion-selective membranes", Inst. ChE (London), Symp. on Less Common Means of Separation, 1963, p. 48.
12. Rosenberg, N.W. and Tirrell, C.E., "Limiting currents in membrane cells", IEC 49 780 (1957).
13. Cowan, D.A. and Brown, J.H., "Effect of turbulence on limiting current in electrodialysis cells", IEC 51 1445 (1959).
14. Kitamoto, A. and Takashima, Y., "Ionic mass transfer in turbulent flow by electrodialysis with ion exchange membranes", J. Ch.E. Japan 3 182 (1970).
15. Ibid., "Transfer rates in electrodialysis with ion exchange membranes", Desalination 9 51 (1971).
16. Forgacs, C., et. al., "Polarization at ion exchange membranes in electrodialysis", Desalination 10 181 (1972).
17. Yamake, T. and Seno, M., "The concentration polarization effect in ion exchange membrane electrodialysis", Desalination 2 148 (1967).
18. Klyachko, V.A. and Ushakov, L.D., "Hydraulic principles for the design of electrodialysis desalination plants", Desalination 2 279 (1967).

19. Cowan, D.A., "Interaction of technical and economic demands in the design of larger scale electrodialysis demineralizers", Saline Water Conversion, ACS Adv. in Chem. No. 27, 1960, p. 224.
20. Probstein, R.F., "Desalination: Some fluid mechanical problems", Trans. ASME, Jnl. Basic Eng., 94D 286 (1972).
21. Sonin, A.A. and Probstein, R.F., "A hydrodynamic theory of desalination by electrodialysis", Desalination 5 293 (1963).
22. Ibid., "Comments on ionic mass transfer rates in electrodialysis", J. Ch.E. Japan 4 283 (1971).
23. Grossman, G. and Sonin, A.A., "Experimental study of the effects of hydrodynamics and membrane fouling in electrodialysis", Desalination, 10 157 (1972).
24. Probstein, R.F., Sonin, A.A., and Gur-Arie, E., "A turbulent flow theory of electrodialysis", Desalination 11 165 (1972).
25. Grossman, G. and Sonin, A.A., "Membrane fouling in electrodialysis: A model and experiments", Desalination 12 107 (1973).
26. Sonin, A.A. and Isaacson, M.S., "Optimization of flow design in forced flow electrochemical systems, with special application to electrodialysis", IEC Proc. Des. Dev 13 241 (1974).
27. Isaacson, M.S. and Sonin, A.A., "Sherwood number and friction factor correlations for electrodialysis systems, with application to process optimization", IEC Proc. Des Dev 15 313 (1976).

F. Reverse Osmosis Desalination

1. Carter, J.W., et. al., "Concentration polarization in reverse osmosis systems under laminar conditions. Effect of surface roughness and fouling", Ch. Eng. Sci. 29 1651 (1974).
2. Ibid., "The effect of finite channel width on concentration polarization in reverse osmosis under laminar flow conditions", Ch. Eng. Sci. 30 1190 (1975).
3. Dresner, L., "Boundary layer buildup in the demineralization of salt water by reverse osmosis", Report ORNL-3621, May, 1964.
4. Srinivasan, S., Tien, C. and Gill, W.N., "Simultaneous development of velocity and concentration profiles in reverse osmosis systems", Office of Salnic Water R and D Prog. Report No. 243, March, 1967.
5. Johnson, T.S. and McCutchen, J.W., "Concentration polarization in the reverse osmosis desalination of sea water", Desalination 10 147 (1972).

6. Liu, M.K., "Iterative analysis of a continuous system for desalination by reverse osmosis", Desalination 9 181 (1971).
7. Hendricks, T.J. and Williams, F.A., "Diffusion-layer structure in reverse osmosis channel flow", Desalination 9 155 (1971).
8. Winograd, Y. and Solan, A., "Concentration build-up in reverse osmosis in turbulent flow", Desalination 7 97 (1969/70).
9. Strathmann, H. and Keilin, B., "Control of concentration polarization in reverse osmosis desalination of water", Desalination 6 174 (1969).
10. Srinivasan, S. and Tien, C., "Natural convection effect in reverse osmosis", Desalination 10 273 (1972).
11. Sherwood, T.K., et. al., "Salt concentration at phase boundaries in desalination by reverse osmosis", IEC Fund. 4 113 (1965); M.I.T. Desalination Research Lab. Report No. 295-1, August 8, 1963.
12. Brian, P.L.T., "Concentration polarization in reverse osmosis desalination with variable flux and incomplete salt rejection", IEC Fund. 4 439 (1965).
13. Shaw, R.A., et. al., "Reverse osmosis: increased productivity by reduction of concentration polarization in laminar flow reverse osmosis using intermediate non-rejecting membrane sections", Desalination 11 189 (1972).
14. Gill, W.W., et. al., "Boundary layer effects in reverse osmosis desalination", IEC Fund. 5 367 (1966).
15. Srinivasan, S. and Tien, C., "A finite difference solution for reverse osmosis in turbulent flow", Desalination 7 51 (1969/70).
16. Ibid., "A simplified method for the prediction of concentration polarization in reverse osmosis operation for multicomponent systems", Desalination 7 133 (1970).
17. Ibid., "Reverse osmosis desalination in tubular membrane duct", Desalination 3 5 (1967).

APPENDIX 5-5

FLOW DISTRIBUTION AND PRESSURE DROP IN REDOX CELL STACKS

This appendix reviews a general approach developed to analyze intra-stack flow distribution and stack pressure drop. Relationships are described between local flow rates and point-by-point pressures at sections within the manifolds and across the cells. Specific equations are given for calculating the various component pressure drop terms. Finally, computational procedures are suggested for solving large-scale stack flow distribution problems.

A closed-set of equations was derived for the flow rate-pressure drop analysis. The manifold analysis includes an assessment of local frictional pressure drop losses and the effects of momentum recovery on pressure at each flow branch point (into or out of a cell). This analysis is an expanded version of the perforated-pipe distribution problem described by Acrivos (48) and Greskovich (49). Using the idealized four cell stack in Figure 1 as an example, the following equations apply:

• Momentum balance in lower manifold

$$L^{P_1^o} - L^{P_1'} = \frac{k_m \rho}{g_c A_m^2} \left[Q_T^2 - (Q_T - Q_1)^2 \right] \quad (1)$$

$$L^{P_2^o} - L^{P_2'} = \frac{k_m \rho}{g_c A_m^2} \left[(Q_T - Q_1)^2 - (Q_T - Q_1 - Q_2)^2 \right] \quad (2)$$

$$L^{P_3^o} - L^{P_3'} = \frac{k_m \rho}{g_c A_m^2} \left[(Q_T - Q_1 - Q_2)^2 - (Q_T - Q_1 - Q_2 - Q_3)^2 \right] \quad (3)$$

• Momentum balance in upper manifold

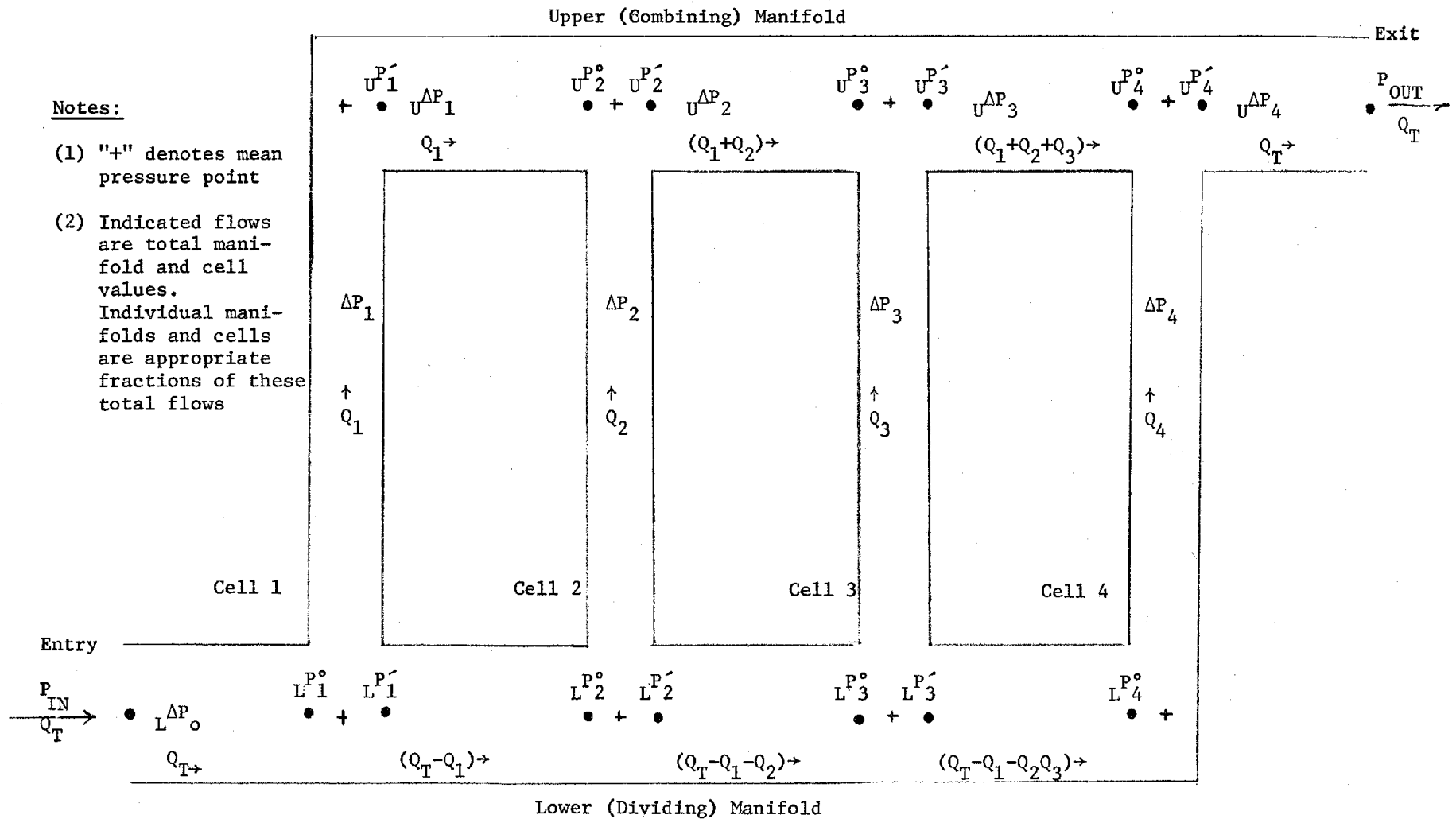
$$U^{P_2^o} - U^{P_2'} = \frac{k_m \rho}{g_c A_m^2} \left[Q_1^2 - (Q_1 + Q_2)^2 \right] \quad (4)$$

$$U^{P_3^o} - U^{P_3'} = \frac{k_m \rho}{g_c A_m^2} \left[(Q_1 + Q_2)^2 - (Q_1 + Q_2 + Q_3)^2 \right] \quad (5)$$

$$U^{P_4^o} - U^{P_4'} = \frac{k_m \rho}{g_c A_m^2} \left[(Q_1 + Q_2 + Q_3)^2 - Q_T^2 \right] \quad (6)$$

Figure 1

Idealized Four Cell Flow Network



• Flow friction pressure drop in lower manifold*

$$P_{IN} - L^{P^{\circ}}_1 = L^{\Delta P}_o = f(Q_T)^n \quad (7)$$

$$L^{P'}_1 - L^{P^{\circ}}_2 = L^{\Delta P}_1 = f(Q_T - Q_1)^n \quad (8)$$

$$L^{P'}_2 - L^{P^{\circ}}_3 = L^{\Delta P}_2 = f(Q_T - Q_1 - Q_2)^n \quad (9)$$

$$L^{P'}_3 - L^{P^{\circ}}_4 = L^{\Delta P}_3 = f(Q_T - Q_1 - Q_2 - Q_3)^n \quad (10)$$

• Flow friction pressure drop in upper manifold*

$$U^{P'}_1 - U^{P^{\circ}}_2 = U^{\Delta P}_1 = f(Q_1)^n \quad (11)$$

$$U^{P'}_2 - U^{P^{\circ}}_3 = U^{\Delta P}_2 = f(Q_1 + Q_2)^n \quad (12)$$

$$U^{P'}_3 - U^{P^{\circ}}_4 = U^{\Delta P}_3 = f(Q_1 + Q_2 + Q_3)^n \quad (13)$$

$$U^{P'}_4 - P_{OUT} = U^{\Delta P}_4 = f(Q_T)^n \quad (14)$$

• Cell (inter-tie) pressure drop**

$$\frac{L^{P^{\circ}}_1 + L^{P'}_1}{2} - U^{P'}_1 = \Delta P_1 = f(Q_1)^n \quad (15)$$

$$\frac{L^{P^{\circ}}_2 + L^{P'}_2}{2} - \frac{U^{P^{\circ}}_2 + U^{P'}_2}{2} = \Delta P_2 = f(Q_2)^n \quad (16)$$

$$\frac{L^{P^{\circ}}_3 + L^{P'}_3}{2} - \frac{U^{P^{\circ}}_3 + U^{P'}_3}{2} = \Delta P_3 = f(Q_3)^n \quad (17)$$

$$L^{P^{\circ}}_4 - \frac{U^{P^{\circ}}_4 + U^{P'}_4}{2} = \Delta P_4 = f(Q_T - Q_1 - Q_2 - Q_3)^n \quad (18)$$

* Functional relationships here depend on nature of flow and are discussed below.

** Cell pressure drop comprises several terms, discussed below.
Indicated ΔP is value between mean pressure points, denoted "+" in Figure 1.

This closed set of 18 equations presumably can be solved to yield values for the 18 unknowns listed below, given the total flow rate, Q_T , the inlet pressure, P_{IN} , and the stack geometry:

$$Q_1, Q_2, Q_3$$

$$L^{P^o}_1, L^{P^o}_2, L^{P^o}_3, L^{P^o}_4$$

$$L^{P^{\wedge}}_1, L^{P^{\wedge}}_2, L^{P^{\wedge}}_3$$

$$U^{P^o}_2, U^{P^o}_3, U^{P^o}_4, P_{OUT}$$

$$U^{P^{\wedge}}_1, U^{P^{\wedge}}_2, U^{P^{\wedge}}_3, U^{P^{\wedge}}_4$$

Overall stack ΔP can then be calculated as: $\Delta P_{STACK} = P_{IN} - P_{OUT}$. The flow distribution among cells is also obtained directly.

These equations assume fully-developed flow in the manifolds between the cells. Fully-developed flow probably will not be achieved with real stack geometries having small inter-cell spacing. However, suitable empirical adjustment factors could be derived, based on future experimental flow distribution data.

The functional relationships between flowrate, cell geometry and pressure drop must be defined before the flow friction equations can be solved. In general, these relations will be different for local laminar or turbulent flow conditions. Cell and manifold pressure drop contributions were analyzed including the effects of:

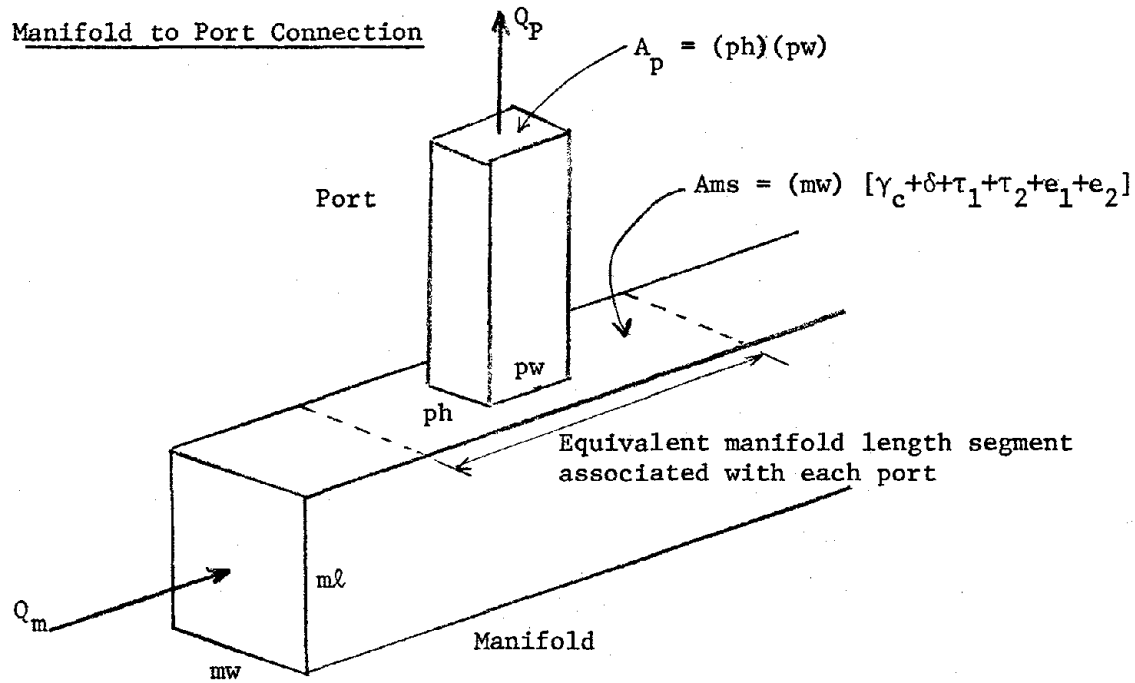
- + Contraction from the entry manifold into the entry port
- + Flow through the entry port
- + Expansion into the active cell area
- + Flow in the active cell area
- + Contraction into the exit port
- + Flow through the exit port
- + Expansion into the exit manifold
- + Overall change in elevation between manifolds
- + Flow in manifolds between ports

The manifold and cell flows involved are shown in Figure 2. Table 1 lists the nomenclature used in the analysis. The assumed cell geometry is the same as that employed in the Stage 2 Model. Further description of this Redox cell design is given in the Stage 2 Model documentation package, found in Volume 2.

Figure 2

Manifold and Cell Flows

Manifold to Port Connection



Port to Cell Connection

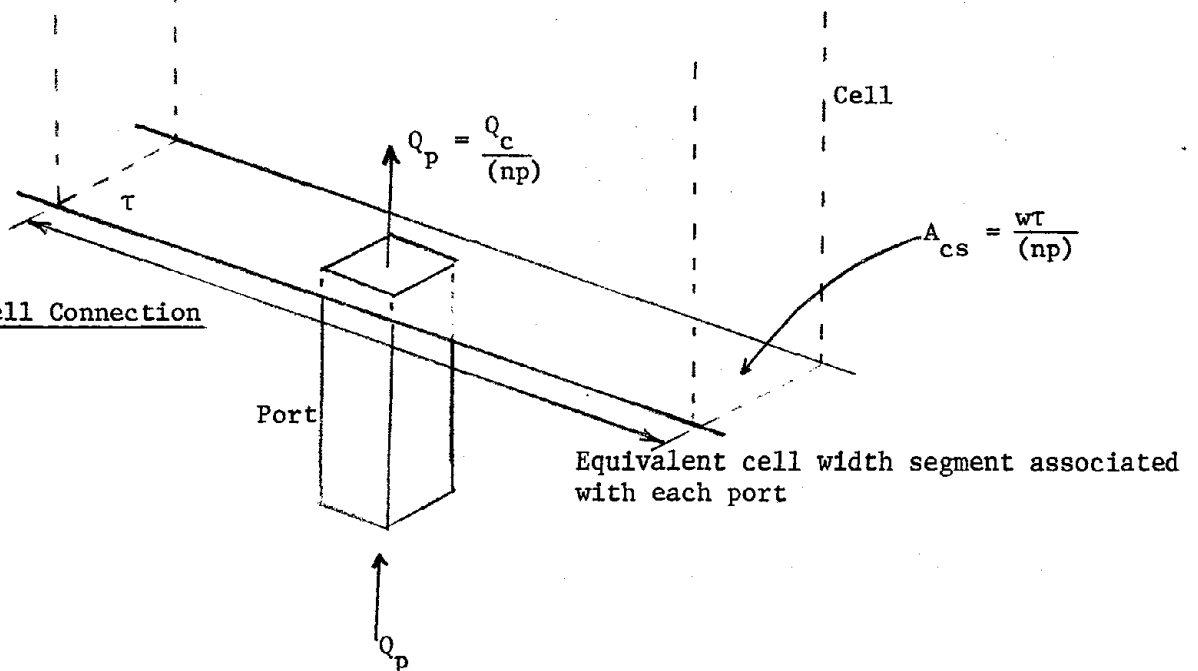


Table 1

Nomenclature for Stack Flow Analysis*

A = Area: A_p = Individual port flow area = (ph)(pw)
 A_m = Individual manifold flow area = (mw)(ml)
 A_{ms} = Equivalent manifold-side area segment associated with each port = (mw) $[\gamma_c + \delta + \tau_1 + \tau_2 + e_1 + e_2]$
 A_{cs} = Equivalent cell-side area segment associated with each port = $\frac{w\tau}{(np)}$

Q = Flow rate: Q_T = Total stack flow rate
 Q_c = Cell flow rate (total, thru area A_c)
 Q_m = Flow rate thru individual manifold.
 Note $Q_m = \frac{Q_T}{(nm)}$ at entry and exit length of manifold.
 Q_i = Flow rate thru i_{th} cell manifold segment
 Q_p = Flow rate thru individual port = $\frac{Q_c}{(np)}$
 Note that all ports associated with an individual cell are assumed to have the same flow rate.

d_h = Hydraulic diameter of duct:

$$d_h = \frac{2(mw)(ml)}{(mw)+(ml)} \text{ for manifold flow}$$

$$d_h = \frac{2(ph)(pw)}{(ph)+(pw)} \text{ for port flow}$$

$$d_h = \frac{2\tau w}{\tau + w} \text{ for cell (total) flow}$$

P = Pressure

Re = Reynolds numbers = $\frac{d_h \rho Q}{\mu A}$; Turbulent flow assumed at Re > 3000

ΔZ = Difference in elevation between lower and upper manifolds

* See Stage 2 Model documentation package for further definition of cell design parameters.

Table 1 (Continued)

g = Acceleration due to gravity

g_c = Dimensional constant = $32.17 \text{ (lb mass)(ft)/(lb force)(sec}^2\text{)}$, in engineering units.

ρ = Solution density

μ = Solution viscosity

k = Laminar flow contraction coefficient (See Table 4)

ξ = Laminar flow ΔP factor (See Table 4)

K_{CL}, K_{CU} = Turbulent flow contraction coefficients for flow from lower manifold to entry port and from cell to exit port, respectively (See Table 5)

f_p, f_m, f_c = Turbulent flow friction factors for port, manifold and cell zones, respectively (See Table 6)

k_m = Momentum recovery coefficient = 0.7

L = Flow path length: L_p = Port length = $(\ell_2 + \ell_3)$ or $(\ell_2 + \ell_5)$

L_m = Equivalent manifold length between ports
 $= \gamma_c + \delta + r_1 + r_2 + e_1 + e_2$

L_c = Cell (total) length = L

Subscripts: p = Port

m = Manifold

c = Cell

s = Segment

Suitable equations for calculating the total pressure drop thru the Redox cell are given in Table 2. Lundgren's analysis for contraction and frictional losses for laminar flow in rectangular ducts was used(50). Perry's Handbook was used for turbulent flow expansions and contractions and friction factors(51). Here, the cell pressure drop is calculated as: Cell ΔP = Static Head + Entry Port ΔP + Active Cell Area ΔP + Exit Port ΔP . Similarly, the manifold pressure drop relations (for flow between port locations) are given in Table 3. Values of the factors used to calculate the entrance and flow friction losses for laminar flow in rectangular ducts (ports, cells and manifolds) are given in Table 4. Turbulent flow contraction coefficients are listed in Table 5. Lastly, Table 6 contains equations for calculating turbulent flow friction factors. Consistent units should be used throughout. This analysis has assumed conventional engineering units.

A fully-programmed version of the flow distribution analysis would involve the following steps:

- Initial assumption of laminar flow in all zones and selection of appropriate ΔP equation terms.
- Solution of the general form (1→1 cells) of the ΔP equations presented earlier, perhaps using Crout's method, as in the shuntage current model. The computational procedures noted in Attachment 1 may be required due to the non-linearity of some of the terms.
- Checks on the flow conditions on all zones to verify laminar conditions.
- Suitable adjustment of the ΔP equation terms, using turbulent flow values, if required.
- Re-solution of the general form ΔP equation, followed by flow condition checks. This procedure would be repeated until calculated flow conditions matched assumed flow conditions.

Additional discussion of mathematical techniques that could be used to carry out the flow distribution analysis is presented in Attachment 1. Here, two cases are considered:

- Relatively simple ΔP relationships, of the form:

$$\Delta P = KQ^2$$

- The complex ΔP relationships, discussed above.

Table 2

Cell Flow Pressure Drop Relations⁽¹⁾

Cell Zone	Flow Condition	ΔP Component	ΔP Relation
Overall	-	Static Head	$\frac{\rho}{g_c} \Delta Z$
Entry Port	Laminar	Contraction + Flow Friction + Expansion into Cell	$\frac{\rho}{2g_c} \left(\frac{Q_p}{A_p} \right)^2 \left[\frac{\xi_p}{(Re)_p} \left(\frac{L_p}{(d_h)_p} \right) + k+1 \right]$ $\frac{\rho}{g_c} \left(\frac{Q_p}{A_p} \right)^2 \left(1 - \frac{A_p}{A_{cs}} \right)^2$
	Turbulent	Contraction + Flow Friction + Expansion into Cell	$\frac{K_{CL} \rho}{2g_c} \left(\frac{Q_p}{A_p} \right)^2$ $\frac{\rho}{2g_c} \left(\frac{Q_p}{A_p} \right)^2 f_p \frac{L_p}{(d_h)_p}$ See laminar case
Active Cell Area	Laminar	Flow Friction	$\frac{\rho}{2g_c} \left(\frac{Q_c}{A_c} \right)^2 \frac{\xi_c}{(Re)_c} \frac{L_c}{(d_h)_c}$
	Turbulent	Flow Friction	$\frac{\rho}{2g_c} \left(\frac{Q_c}{A_c} \right)^2 f_c \frac{L_c}{(d_h)_c}$
Exit Port	Laminar	Contraction + Flow Friction + Expansion into Manifold	$\frac{\rho}{2g_c} \left(\frac{Q_p}{A_p} \right)^2 \left[\frac{\xi_p}{(Re)_p} \left(\frac{L_p}{(d_h)_p} \right) + k+1 \right]$ $\frac{\rho}{g_c} \left(\frac{Q_p}{A_p} \right)^2 \left(1 - \frac{A_p}{A_{ms}} \right)^2$
	Turbulent	Contraction + Flow Friction + Expansion into manifold	$\frac{K_{CU} \rho}{2g_c} \left(\frac{Q_p}{A_p} \right)^2$ See entry port turbulent case $\frac{\rho}{2g_c} \left(\frac{Q_p}{A_p} \right)^2 \left(1 - \frac{A_p}{A_{ms}} \right)^2$

(1) Total cell ΔP equals sum of ΔP contributions due to: Static Head, Entry Port, Active Cell Area and Exit Port. Note Q_c and Q_p apply to ith cell.

Table 3

Manifold Flow Pressure Drop Relations⁽¹⁾

<u>Flow Condition</u>	<u>ΔP Component</u>	<u>ΔP Relation</u>
Laminar	Flow Friction ⁽²⁾⁽³⁾	$\frac{\rho}{2g_c} \left(\frac{Q_i}{A_m} \right)^2 \left[\frac{\xi_m}{(Re)_m} \left(\frac{L_m}{(d_h)_m} \right) \right]$
Turbulent	Flow Friction ⁽⁴⁾	$\frac{\rho}{2g_c} \left(\frac{Q_i}{A_m} \right)^2 f_m \left(\frac{L_m}{(d_h)_m} \right)$
All	Momentum Recovery ⁽⁵⁾	$- k_m \frac{\rho}{g_c} \left[\left(\frac{Q_i}{A_m} \right)^2 - \left(\frac{Q_{i+1}}{A_m} \right)^2 \right]$

- (1) Pressure drop thru a manifold equals the algebraic sum of flow friction and momentum recovery contributions, calculated using local manifold flow rates, adjusted for out-flows and in-flows.
- (2) Values of ξ are listed in Table 4. The aspect ratio should be based on the manifold dimensions (mw) and ml).
- (3) The equivalent manifold length, L_m , is the distance between 2 ports, i.e., $L_m = \gamma_c + \delta + \tau_1 + \tau_2^m + e_1 + e_2$
- (4) The turbulent flow friction factor, f_m , is listed in Table 6.
- (5) The momentum recovery coefficient, k_m , has an approximate value of 0.7.

Table 4

Laminar Flow Entrance Pressure Drop Factors⁽¹⁾

<u>Duct Aspect Ratio</u> ⁽²⁾	<u>ξ</u>	<u>k</u>
0.0	96.000	0.6857
0.05	89.908	0.7613
0.1	84.675	0.8392
0.125	82.339	0.8788
0.167	78.809	0.9451
0.25	72.931	1.0759
0.4	65.472	1.2815
0.5	62.192	1.3829
0.75	57.886	1.5203
1.00	56.908	1.5515

(1) Taken from Lundgren (50).

(2) Ratio height/width, b/a as shown:

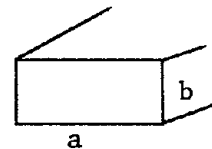


Table 5

Turbulent Flow Contraction Coefficients⁽¹⁾

<u>Flow Area Ratio</u> ⁽²⁾	<u>K_c</u>
0	0.50
0.2	0.45
0.4	0.36
0.6	0.21
0.8	0.07
1.0	0

(1) Taken from Perry (51).

(2) Entry (large) area/Exit (small) area.

Table 5

Turbulent Flow Friction Factors

<u>Flow Zone</u>	<u>Reynolds Number Range</u>	<u>Friction Factor</u>
Ports ⁽¹⁾	$Re > 3000$	$f_p = 0.0014 + \frac{0.125}{(Re)_p^{0.32}}$
Cells and Manifolds ⁽²⁾	$3000 < Re < 10^5$	$f_c, f_m = \frac{0.04}{Re^{0.16}}$
	$Re > 10^5$	$f_c, f_m = 0.0063$

(1) Assumes very smooth walls.

(2) Assumes average roughness walls.

Attachment 1

Techniques for Flow Distribution Analysis

Consider a manifold system consisting of a lower supply manifold, a series of N cells, and an upper exit manifold. The flow rate through the i^{th} cell is denoted as Q_i , the total flow in the system is Q_T or $\sum_{i=1}^N Q_i$. The flow rate in the lower manifold just after the i^{th} cell is $Q_T - \sum_{j=1}^i Q_j$. The flow rate in the upper manifold after the i^{th} cell is $\sum_{j=1}^i Q_j$. Therefore, at any location along the stack, the total flow remains constant at Q_T .

In the simple case assume a pressure drop relationship of the form: $\Delta P = KQ^2$, where K is a resistance term. The flow in the manifold will obey Kirchoff's laws but would not account for pressure changes due to expansion or contraction. Hence a pressure balance around the i^{th} and $i + 1^{\text{st}}$ cells would be:

$$\Delta P (i^{\text{th}} \text{ cell}) + \Delta P (\text{upper manifold}) = \Delta P (i + 1^{\text{st}} \text{ cell}) + \Delta P (\text{lower manifold}) \quad (1)$$

segment segment

$$K_c Q_i^2 + K_m \left(\sum_{j=1}^i Q_j \right)^2 = K_c Q_{i+1}^2 + K_m \left(Q_T - \sum_{j=1}^i Q_j \right)^2$$

$$\text{or,} \quad K_c Q_i^2 + 1 = K_c Q_{i+1}^2 + K_m \left(\sum_{j=1}^i Q_j \right)^2 - K_m \left(Q_T - \sum_{j=1}^i Q_j \right)^2$$

dividing by K_c yields,

$$Q_{i+1}^2 = Q_i^2 + \frac{K_m}{K_c} \left(\sum_{j=1}^i Q_j \right)^2 - \frac{K_m}{K_c} \left[Q_T^2 - 2Q_T \sum_{j=1}^i Q_j + \left(\sum_{j=1}^i Q_j \right)^2 \right]$$

or,

$$Q_{i+1}^2 = Q_i^2 - \frac{K_m}{K_c} \left[Q_T^2 - 2Q_T \sum_{j=1}^i Q_j \right]$$

and finally,

$$Q_{i+1}^2 = Q_i^2 - \frac{K_m Q_T}{K_c} \left[Q_T - 2 \sum_{j=1}^i Q_j \right] \quad (2)$$

for $i = 1, N$
 where k_c = is the cell resistance
 and k_m^c = is the manifold resistance

To solve for the flow rate distribution in the manifold, one need only to assume a value of Q_1 and recursively solve equation 2 for Q_2 through Q_N . If the sum of all the flows equals Q_T then the assumed value of Q_1 was correct. If not, then the value of Q_1 must be adjusted accordingly.

There are several important points to remember:

- The system, as stated, is symmetrical: i.e.,
 $Q_i = Q_{N+1-i}$
- $Q_i > Q_{i+1}$, for $i = 1, N/2$
- As $K_m/K_c \rightarrow 0$, $Q_i = Q_{i+1} = Q_{i+2} \dots \rightarrow Q_T/N$
- As $K_m/K_c \rightarrow 1$, the solution technique, as stated, becomes unstable, i.e., when equation (2) is solved for Q_i with too low an estimate of Q_1 a negative value of Q_i^2 will eventually arise; if Q_1 is too high, the values of Q_i grow too large. Unfortunately, a too low and too high value of Q_1 may differ only in the sixth significant figure.

A more sophisticated model of the manifold system would use a slightly more complicated technique. Actually, there are two possible approaches to take to solve the more detailed case: One of these is somewhat recursive but is really a marching technique and the other is a simultaneous solution technique.

The marching technique would assume a value of Q_1 and would calculate the pressure drop through the first cell based upon the proper (laminar or turbulent) pressure drop correlation. It would also be able to do the same for the upper and lower manifolds. At this time, the pressure drop across the second cell is known, but not the flow rate. Therefore, an iterative procedure would assume a value of the flow rate in the second cell until the desired pressure drop was calculated. This procedure would repeat itself, marching down the system.

The simultaneous solution technique solves the nonlinear Kirchhoff equations iteratively. The equations consist of the mass balances and loop equations. The mass balances are at each cell entrance and exit. The loop equations state that the pressure drop around each loop (two adjacent cells and the connecting manifolds) is zero, i.e., equation 1. Once the latest estimates of flow rate are known, the coefficients for the loop equations can be recalculated for the next iteration. There is an inherent advantage in this approach since most of the equations (mass balances) are linear which tend to stabilize the solution.

This more complex model would be able to handle telescoping manifolds or any other variations in the system which the simplified version could not, such as pressure rises at the ports of the inlet manifold. Either approach has this capability, but for system with $N > 20$ or $K_m/K_c > .1$ the simultaneous solution approach is recommended.

APPENDIX 6

PRELIMINARY TESTING OF THE STAGE 2 MODEL

Only preliminary testing of the Stage 2 Model was carried out. Initial results, using conservative base-line values for key parameters, were discouraging. Very low Redox cell power outputs were predicted, requiring more than 100 Redox trailers to meet imposed discharge power levels of 5-20 MW. Insufficient time was available to fully digest these results. The great numbers of parameters involved, and the substantial interactions among these parameters, makes diagnosis difficult. The following discussion highlights these initial results and suggests future courses of action.

• Key Stage 2 Model Parameters

The key base-line parameter values selected for study are listed below:

+ Cell Frame Dimensions

Active cell width, W = 40 cm
Active cell length, L = 20 cm
Entry & exit port lengths, ℓ_3 and ℓ_5 = 1 cm (increased to 5 cm)

+ Cell Component Dimensions

Flow zone thickness, τ_1 and τ_2 = 0.2 cm
Membrane thickness, δ = 0.01 cm

+ Cell, Stack and Trailer Assembly Factors

Number of cells per sub stack, n_s = 10
Number of sub stacks per stack, n_{ss} = 20

+ System Operational Factors

Solution flow rate factor, f_1 and f_2 = 2
Maximum permitted cell voltage, E_{\max} = 1.6 v (increased to 2.0 v)

Reactant utilization factors:

Upper concentration limit, β_{\max} = 0.9 (decreased to 0.677)
Lower concentration limit, β_{\max} = 0.1 (increased to 0.333)

+ Reactant Properties

Electrons transferred per mole, Z_1 and Z_2 = 1

Reaction standard potentials:

$(E_o)_1$ = 0.9 v

$(E_o)_2$ = 0.1 v

Exchange current density, $(i_o)_1$ and $(i_o)_2$ = 0.001 amps/cm²
(increased to 0.01 $\frac{\text{amp}}{\text{cm}^2}$)

Reaction transfer coefficients, α = 0.5 (all)

Reactant diffusivity, D_1 and D_2 = 5×10^{-5} cm²/sec.

+ Miscellaneous Factors

Membrane resistivity, ρ = 25 Ω cm

Mass transfer augmentation factors, ψ_1 and ψ_2 = 1

Stack electrical connection: All stacks (decks) in series within a trailer

• Preliminary Findings

Use of the above factors resulted in very low average discharge current density (\bar{i}) operation, yielding low power output. Observation of several of the debug printouts showed that there is a pronounced variation in local current density down the cell. This result was expected. Mass transfer conditions are good at the cell inlet, resulting in high local current densities (i_{Local}). Further down the cell, the thickening diffusion boundary layer resulted in poorer mass transfer conditions and low local limiting current values. Attempts to improve the mass transfer rates by increasing the flow rate (via the f factor) gave excessive estimates of auxiliary pumping power. This power was suppressed by introducing a new modifying factor, f_p , but values as low as $f_p = 0.1$ still gave somewhat high power requirements. A complete system pressure drop analysis is required to properly estimate the real effect of flow rate on pumping losses. Increasing the mass transfer augmentation factor, ψ , helped, but was not completely successful. Future runs could be made using thinner cells.

Integration of the local current density, over all the Δx distance slices down the cell ($x = 0$ to $x = L$) gave low average current density (\bar{i}). In effect, the lower sections of the cell contributed very little to current generation. In general, the \bar{i} convergence routines were slow, requiring many iterations. Shorter cells should be considered.

It was also found that reactant utilization was poor. The Redox cell performance estimates indicated that very little power could be obtained from relatively depleted solutions. Conversely, it was not possible to continue the charging operation with relatively high state-of-charge solutions. Conditions were not found where a complete inventory restoration could be made. This effect is most pronounced when very short Δt time increments, about 10 minutes, are used as data input.

In addition, relative shuntage current power losses appeared quite high. Increasing the port lengths from 1 to 5 cm helped somewhat, but much additional work is required to develop improved Redox cell configurations.

Lastly, the low stack performance (voltage) coupled with the stack electrical connection (all stacks in series within a Redox trailer) resulted in low voltage designs for the power conditioning section. In turn, this gave very high costs for this section. Consideration should be given to series connections of the Redox trailers for increasing the operating voltage of the power conditioner.

Of course, many of these results were expected. The chief function of the Stage 2 Model is to evaluate the effect of concentration and time-dependent Redox cell performance. Evidently, considerable optimization work remains to explore parameter values that yield satisfactory predictions.

7. REFERENCES

1. Kalhammer, F. R., "Energy Storage: Incentives and Prospects for Its Development", Paper presented at 168th ACS Meeting Division of Fuel Chemistry, Vol. 19, No. 4, Atlantic City, September 8-13, 1974.
2. Kalhammer, F. R. and Zygielbaum, P.S., "Potential for Large-Scale Energy Storage", ASME Publication 74-WA/Ener-9.
3. Kalhammer, F. R. and Schneider, T. R., "Energy Storage", Chapter in Annual Review of Energy, Vol. 1, edited by J. M. Hollander and M. K. Simmons, Annual Reviews, Inc., Palo Alto, California, 1976, p. 311.
4. Public Service Electric and Gas Company, "An Assessment of Energy Storage Systems Suitable for Use by Electric Utilities", EPRI EM-264, Project 225, ERDA E(11-1)-2501, Final Report, 2 Vols. July, 1976.
5. Lewis, P. A. and Zemkoski, J., "Prospects for Applying Electrochemical Energy Storage in Future Electric Power Systems", Paper Presented at 1973 IEEE Intercon Technical Papers, Session 13, March 26-30, 1973.
6. El-Badry, Y. Z. and Zemkoski, J., "The Potential for Rechargeable Storage Batteries in Electric Power Systems", Paper presented at the 9th Intersociety Energy Conversion Engineering Conference, San Francisco, California, August 26-30, 1974.
7. Crouch, D.A., Jr., Werth, J. "Batteries and the Economics of Load Leveling in Large Power Systems", Paper presented at IEEE PES Winter Meeting, New York, January 28-February 2, 1973.
8. Douglas, D. L., "Batteries for Energy Storage", ACS Division of Fuel Chem. 19 (4), 135 (1974).
9. Heredy, L. A., and Parkins, W. E., "Lithium-Sulfur Battery Plant for Power Peaking", IEEE Conference paper C 72-234-8, January 30, 1972.
10. Rosengarten, W.E. et al., "Wanted: Load Leveling Storage Batteries", Paper presented at Electrochemistry Society, Miami Beach, October 1972.
11. Ivins, R. O. et al., "Design of a Lithium/Sulfur Battery for Load Leveling on Utility Networks", Paper presented at IEEE Symposium, Charlotte, N. Carolina, April 8-10, 1975.
12. Kyle, M. L. et al., "Lithium/Sulfur Batteries for Off-Peak Energy Storage: A Preliminary Comparison of Energy Storage and Peak Power Generation Systems", Argonne National Laboratory Report No. ANL-7958.
13. Kangro, W. and Pieper, H., Electrochem. Acta. 7:435 (1962).

14. Thaller, L. H., "Electrically Rechargeable Redox Flow Cell", Proceedings 9th IECEC, 1974, p. 924.
15. Beccu, Klaus, D., "The Satisfaction of Future Peak Demand for Electrical Power by Means of Electrochemical Power Storage Units", Paper presented at the GDCh Subject Group "Applied Electrochemistry", October 4-5, 1973, Ludwigschafen/Rh.
16. Beccu, K. D., Prepared Discussion for 9th World Energy Conference, Detroit, 1974.
17. Beccu, K. D., Chem. Ing. Tech. 46:95 (1974).
18. Warshay, M., and Wright, L. O., "Cost and Size Estimates for a Redox Bulk Energy Storage Concept", NASA TM X-3192, February, 1975.
19. Ashimura, S. and co-authors, Denki Kagaku, 36:872 (1968); 37:54, 119 (1969); 39:944 (1971); 40:50, 443 (1972); 43:214 (1975); 44:46, 114 (1976); 45:42 (1977).
20. Liu, C.C., "Annual Report on the Research and Development of a Soluble Reactants and Products Battery System", NASA Grant NSA-3010, May 1, 1974 - July 31, 1975.
21. Lahoda, E. J., "Development of a Soluble Reactants and Products Secondary Battery", Ph.D. Thesis, Univ. Of Pittsburgh, 1974.
22. Werth, J., et al., "The Sodium Chloride Battery," Abstract No. 242, Electrochemical Society, Dallas Meeting, October, 1975, p. 611.
23. Electric Power Research Institute, "Storage Batteries: The Case and the Candidates", EPRI Journal, 1(8) 6 (October, 1976).
24. Birk, J. R. and Werth, J., "Sodium Chloride Battery Development Program for Load Leveling", ESB, Inc., Report EPRI/EM-230, December, 1975.
25. Cerra, F., "Utility Plan on Peak Use is Ordered", N. Y. Times, February 15, 1977.
26. Sulzberger, V. T. and Zemkoski, J., "The Potential for Application of Energy Storage Capacity on Electric Utility Systems in the United States - Parts I and II," Part I - IEEE Winter Power Meeting, New York, N. Y., January 1976, and Part II - submitted to IEEE for review for 1976 Summer Power Meeting, Portland, Oregon.
27. Wood, W., Bhavaraju, M. P., Solowski, S. J., and Widman, D. C., "A Probabilistic Approach to Off-Peak Electric Energy Evaluation", IEEE Meeting, New York, N. Y., January, 1976.
28. Huse, R. A., Schneider, T. R., Snow, R. V., Sulzberger, V. T., and Zemkoski, J., "The Application of Energy Storage Systems to Electric Utilities in the United States", 1976 CIGRE Biennial Conference, Paris, France, August 25 - September 4, 1976.

29. Merriam, M. F., "Wind Energy for Human Needs", Technology Review, January, 1977, p. 28.
30. Simmons, W. D., Wind Power, Energy Technology Review No. 6, Noyes Data Corp., Park Ridge, New Jersey, 1975.
31. Andrews, J. W., "Energy-storage requirements reduced in coupled wind-solar generating systems", Solar Energy 18 73 (1976).
32. Nelson, V., et al., "Potential for wind generated power in Texas", PB-243, 349, October 15, 1974.
33. Jaya Devaiah, T. S., "Generation Schemes for Wind Power Plants", IEEE Trans. Aerospace and Electronics Systems AES-11 543 (1975).
34. Reed, J. J., "Assessment of the state-of-the-art of feeding wind-generated electricity into utility power grids", AD A024278, March 8, 1976.
35. Hundermann, A. S., "Wind Power (Citations from the NTIS Base)," NTIS/PS-76/0358/2WE, May, 1976.
36. Ibid, "Wind Power (Citations from the Engineering Index Data Base)," NTIS/PS-76/0359/OWE, May, 1976.
37. Jayadev, T.S. and Smith, R. T., "Wind-Powered Electric Utility Plants" ASME Paper No. 75-WA/Pet-1.
38. Thaller, L., "NASA Review of CY'76 Redox Program", presented at First Annual ERDA Battery Contractor's Coordination Meeting, Germantown, Maryland, January 27-28, 1977.
39. Wood, P., "AC/DC Power Conditioning and Control Equipment for Advanced Conversion and Storage Technology", Westinghouse Electric Corp., Report No. EPRI 390-1-1, August, 1975.
40. Bockris, J. O'M. and Reddy, A. K. N., Modern Electrochemistry, Vol. 2, Plenum Press, New York, 1970.
41. Bockris, J. O'M. and Nagy, Z., "Symmetry Factor and Transfer Coefficient", J. Chem. Ed., 50 839 (1973).
42. Austin, L. G., "The Electrochemical Theory of Fuel Cells," Chapter in Handbook of Fuel Cell Technology, C. Berger, ed., Prentice-Hall, Englewood Cliffs, N. J., 1968, p. 178.
43. Landau, V. and Tobias, C. W., "Mass Transport and Current Distribution in Channel Type Electrolyzers in the Laminar and Turbulent Flow Regimes." Electrochemical Society Extended Abstracts for May, 1976 Meeting. Washington, D.C. p. 663.
44. Helfferich, F., Ion Exchange, McGraw-Hill, New York, 1962.
45. Kunin, R., Ion Exchange Resins, 2nd Edition, Wiley, New York, 1958.
46. Wilson, J. R., id., Demineralization by Electrodialysis, Butterworths, London, 1960.

47. Prokopius, P.R., "Model for Calculation Electrolytic Shunt Path Losses in Large Electrochemical Energy Conversion Systems," NASA TM X-3359, April, 1976.
48. Acrivos, A., et al., "Flow Distributions in Manifolds," Chem. Eng. Sci. 10 112 (1959)
49. Greskovich, E. J. and O'Bara, J. T., "Perforated-Pipe Distributors," IEC Process Design and Deve. 7 593 (1968).
50. Lundgren, T.S., et al., "Pressure Drop Due to the Entrance Region in Ducts of Arbitrary Cross Section," Trans. ASME 86D 620 (1964).
51. Perry, R. H. and Chilton, C. G., Chemical Engineers' Handbook, Fifth Edition, McGraw-Hill, New York, 1973.
52. Rodhe, J. E. and Knoll, R. H., "Analysis of a Solar Collector Field Water Flow Network", NASA Technical Memo TM X-3414, Lewis Research Center, Cleveland, Ohio, August, 1976.
53. Bajura, R. A. and Jones, E. H., "Flow Distribution Manifolds", Tr. ASME, Jnl. Fluids Eng., December, 1976, p. 654.
54. Jeppson, R. W., Analysis of Flow in Pipe Networks, Ann Arbor Science, Ann Arbor, Michigan, 1976.
55. Alexander, S. S., et. al., "Anion Selective Membrane", NASA CR-134931, Ionics, Inc., Undated.
56. Lacey, R. E. and Cowsar, D. R., "Development of Anion-Selective Membranes", NASA-CR-134932, Southern Research Institute, October, 1975.
57. Sumner, J., "Rubber Fabrications are Full of Bounce", The Engineer, December 9, 1976, p. 32.
58. Lock, J., "Inflated Concrete Plant Buildings", Processing, December, 1974, p. 10.
59. Anon, "Air Bubbles Find a Wider Market", Business Week, December 6, 1976, p. 42R.

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) REDOX BULK ENERGY STORAGE SYSTEM STUDY		5. TYPE OF REPORT & PERIOD COVERED VOLUME I - FINAL REPORT 18 Feb 1976 - 30 Jan 1977
7. AUTHOR(s) G. Ciprios W. Erskine, Jr. P. G. Grimes		6. PERFORMING ORG. REPORT NUMBER EXXON/GRU.1BH.77
9. PERFORMING ORGANIZATION NAME AND ADDRESS Exxon Research and Engineering Company Government Research Laboratories P.O. Box 8, Linden, New Jersey 07036		8. CONTRACT OR GRANT NUMBER(s) NAS3-19776
11. CONTROLLING OFFICE NAME AND ADDRESS National Aeronautics and Space Administration Lewis Research Center Cleveland, Ohio 44135		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)		12. REPORT DATE February 10, 1977
		13. NUMBER OF PAGES Volume 1: 198
		15. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE N/A
16. DISTRIBUTION STATEMENT (of this Report) APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED		
17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)		
18. SUPPLEMENTARY NOTES		
19. KEY WORDS (Continue on reverse side if necessary and identify by block number) Redox Batteries Computer Models Energy Storage Systems Analysis Electric Utility Operation Electrochemical Devices		
20. ABSTRACT (Continue on reverse side if necessary and identify by block number) Opportunities were found for electrochemical energy storage devices in the U.S. electric utility industry. Application requirements for these devices were defined, including techno-economic factors. A new device, the Redox storage battery was analyzed. The Redox battery features a decoupling of energy storage and power conversion functions. General computer methods were developed to simulate Redox system operations. These studies showed that the Redox system is potentially attractive if certain performance		

SECURITY CLASSIFICATION OF THIS PAGE(When Data Entered)

goals can be achieved. Pathways for reducing the cost of the Redox system were identified.

SECURITY CLASSIFICATION OF THIS PAGE(When Data Entered)